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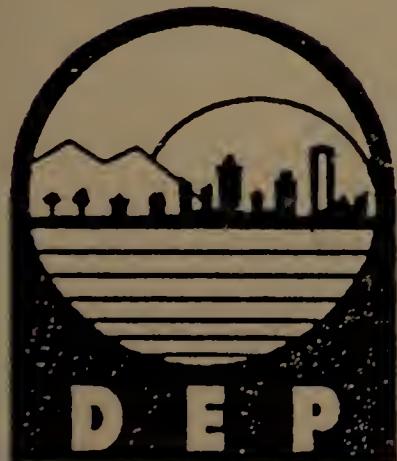
Standard References for Monitoring Wells

Revision/Update 1994- Chapters 7 & 8

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SECTION 7.0
GROUNDWATER MODELING

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
7.1	GROUNDWATER MODELING OVERVIEW	1
7.1-1	Introduction	1
7.1-2	Purpose	1
7.1-3	General Applications	2
7.2	MODELING TERMINOLOGY	3
7.2-1	Terminology	3
7.3	MATHEMATICAL MODELS	6
7.3-1	Types of Models	6
7.3-2	Analytical Models	7
7.3-3	Numerical Models	8
7.3-3.1	Finite-Difference Technique	11
7.3-3.2	Finite-Element Technique	11
7.3-4	Solute Transport Models	12
7.3-5	Application of Numerical Models to Groundwater Flow Problems	14
7.3-6	Modeling Limitations	14
7.4	PROCEDURES FOR CONSTRUCTING A NUMERICAL FLOW MODEL	16
7.4-1	Modeling Team	16
7.4-2	Conceptual Model	17
7.4-3	Selection of an Appropriate Model	19
7.4-4	Data Compilation	20
7.4-4.1	Geometry of the Aquifer System	21
7.4-4.2	Transmissivity	22
7.4-4.3	Storage Coefficients	23
7.4-4.4	Identification of Surface Water Features	23
7.4-4.5	Leakage	23
7.4-4.6	Delineation of Discharge and Recharge Areas	23
7.4-4.7	Piezometric Heads	24
7.4-5	Definition of Boundary and Initial Conditions	24
7.4-6	Construction of the Model Grid	25
7.4-7	Assignment of Parameters to Nodes	26

SECTION 7.0
GROUNDWATER MODELING

TABLE OF CONTENTS (continued)

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
7.5	PROCEDURES FOR RUNNING A NUMERICAL FLOW MODEL	27
7.5-1	Model Calibration	27
7.5-2	Model Validation	28
7.5-3	Sensitivity Analysis	28
7.5-4	Forecasting	29
7.6	REPORTING MODEL RESULTS	30
7.6-1	Presentation of Results	30
7.6-2	Purpose	30
7.6-3	Conceptual Model	30
7.6-4	Data Collection	30
7.6-5	Model Description	30
7.6-6	Assignment of Model Parameters	31
7.6-7	Model Calibration	31
7.6-8	Model Validation	31
7.6-9	Sensitivity Analysis	31
7.6-10	Data Preprocessing and Postprocessing	32
7.6-11	Model Prediction	32
7.6-12	Model Results	32
7.6-13	Model Records	32
REFERENCES	33

SECTION 7.0
GROUNDWATER MODELING

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page No.</u>
7-1	Finite Difference and Finite Element Representations of an Aquifer Region	35
	a. Map View of Aquifer Showing Well Field, Observation Wells, and Boundaries	
	b. Finite difference Grid with Block-Centered Nodes, Where Δx is the Spacing in the x direction, Δy is the Spacing in the y Direction, and b is the Aquifer Thickness	
	c. Finite difference Grid with Mesh-Centered Nodes	
	d. Finite element Mesh with Triangular Elements, Where b is the Aquifer Thickness .	
7-2	Flow Chart to Determine if Modeling is Required	36

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page No.</u>
7-1	Natural Processes that Affect Subsurface Contaminant Transport	37

SECTION 8.1
INTRODUCTION

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.1	INTRODUCTION	1
8.1-1	Document Structure	2
8.1-2	Background Reference Materials	3

SECTION 8.2
SYNOPSIS OF GEOPHYSICAL INVESTIGATION METHODS

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.2-1	SEISMIC METHODS	1
8.2-1.1	Operating Principle	1
8.2-1.2	Applications	1
8.2-1.3	Limitations	2
8.2-2	RESISTIVITY METHOD	2
8.2-2.1	Operating Principle	2
8.2-2.2	Applications	3
8.2-2.3	Limitations	4
8.2-3	SELF-POTENTIAL METHOD	4
8.2-3.1	Operating Principle	4
8.2-3.2	Applications	5
8.2-3.3	Limitations	5
8.2-4	ELECTROMAGNETIC INDUCTION METHOD	5
8.2-4.1	Overview	5
8.2-4.1.1	Terrain Conductivity - Operating Principle	5
8.2-4.1.2	Terrain Conductivity Applications	6
8.2-4.1.3	Terrain Conductivity Limitations	7
8.2-4.1.4	VLF - Operating Principle	7
8.2-4.1.5	VLF - Applications	8
8.2-4.1.6	VLF - Disadvantages	8
8.2-5	GROUND PENETRATING RADAR (GPR)	9
8.2-5.1	Operating Principle	9
8.2-5.2	Applications	9
8.2-5.3	GPR Limitations	9
8.2-6	MAGNETIC METHODS	10
8.2-6.1	Overview	10
8.2-6.2	Applications	11
8.2-6.3	Limitations	11

SECTION 8.2
SYNOPSIS OF GEOPHYSICAL INVESTIGATION METHODS

TABLE OF CONTENTS
(continued)

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.2-7	GRAVITY METHOD	11
8.2-7.1	Overview	11
8.2-7.2	Applications	12
8.2-7.3	Limitations	12

LIST OF FIGURES

<u>Table</u>	<u>Title</u>	<u>Page No.</u>
8.2-1	Comparison of Geophysical Methods	14

SECTION 8.3
BOREHOLE GEOPHYSICAL METHODS

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.3-1	OVERVIEW	1
8.3-2	INTRODUCTION	2
8.3-2.1	Equipment	3
8.3-2.2	Field Procedures	3
8.3-3	PASSIVE BOREHOLE METHODS (NON-PENETRATING)	5
8.3-3.1	Borehole Television Camera Surveys	5
8.3-3.1.1	Principles of Operation	5
8.3-3.1.2	Applications	5
8.3-3.1.3	Equipment	6
8.3-3.1.4	Field Procedures	6
8.3-3.1.5	Interpretation	6
8.3-3.1.6	Advantages and Disadvantages	6
8.3-3.2	Caliper Logging	7
8.3-3.2.1	Principles of Operation	7
8.3-3.2.2	Applications	7
8.3-3.2.3	Equipment	7
8.3-3.2.4	Field Procedures	7
8.3-3.2.5	Interpretation	8
8.3-3.2.6	Advantages and Disadvantages	8
8.3-3.3	Temperature Logging	8
8.3-3.3.1	Principles of Operation	8
8.3-3.3.2	Applications	8
8.3-3.3.3	Equipment	9
8.3-3.3.4	Field Procedures	9
8.3-3.3.5	Interpretation	9
8.3-3.3.6	Advantages and Limitations	9
8.3-3.4	Self Potential (SP)	10
8.3-3.4.1	Principles of Operation	10
8.3-3.4.2	Applications	10
8.3-3.4.3	Equipment	10
8.3-3.4.4	Field Procedures	11
8.3-3.4.5	Interpretation	11
8.3-3.4.6	Advantages and Disadvantages	11

SECTION 8.3
BOREHOLE GEOPHYSICAL METHODS

TABLE OF CONTENTS (continued)

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.3-3.5	Fluid Resistivity	11
8.3-3.5.1	Principles of Operation	11
8.3-3.5.2	Applications	12
8.3-3.5.3	Equipment	12
8.3-3.5.4	Field Procedures	12
8.3-3.5.5	Interpretation	12
8.3-3.5.6	Advantages and Limitations	13
8.3-3.6	Inhole Flow Measurement (Flowmeters)	13
8.3-3.6.1	Principles of Operation	13
8.3-3.6.2	Applications	14
8.3-3.6.3	Equipment	14
8.3-3.6.4	Field Procedures	15
8.3-3.6.5	Interpretation	15
8.3-3.6.6	Advantages and Limitations	16
8.3-4	FORMATION PENETRATING METHODS	17
8.3-4.1	Resistivity Techniques	17
8.3-4.1.1	Principles of Operation	17
8.3-4.1.2	Applications	18
8.3-4.1.3	Equipment	18
8.3-4.1.4	Field Procedures	18
8.3-4.1.5	Interpretation	19
8.3-4.1.6	Advantages and Disadvantages	19
8.3-4.2	Acoustic (Sonic) Methods	20
8.3-4.2.1	Principles of Operation	20
8.3-4.2.2	Applications	22
8.3-4.2.3	Equipment	23
8.3-4.2.4	Field Procedures	23
8.3-4.2.5	Interpretation	24
8.3-4.2.6	Advantages and Disadvantages	24

SECTION 8.3
BOREHOLE GEOPHYSICAL METHODS

TABLE OF CONTENTS (continued)

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.3-4.3	Nuclear (Radiation) Methods	25
8.3-4.3.1	Principles of Operation	25
8.3-4.3.1.1	Natural Gamma-ray Log	25
8.3-4.3.1.2	Gamma-gamma Log	25
8.3-4.3.1.3	Neutron-epithermal-neutron Log	26
8.3-4.3.2	Applications	26
8.3-4.3.3	Equipment	27
8.3-4.3.4	Field Procedures	27
8.3-4.3.5	Interpretation	27
8.3-4.3.6	Advantages and Disadvantages	29
8.3-4.4	Vertical Seismic Profiling (VSP)	29
8.3-4.4.1	Principles of Operation	29
8.3-4.4.2	Applications	30
8.3-4.4.3	Equipment	30
8.3-4.4.4	Field Procedures	31
8.3-4.4.5	Interpretation	31
8.3-4.4.6	Advantages and Disadvantages	32
8.3-5	GLOSSARY	32
REFERENCES	34

SECTION 8.3
BOREHOLE GEOPHYSICAL METHODS

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page No.</u>
8.3-1	Typical Geophysical Logging Setup	38
8.3-2	Caliper Probes	39
8.3-3	Interpretation of Borehole Temperature Profiles .	40
8.3-4	SP Log Example	41
8.3-5	Example of Flowmeter Log	42
8.3-6	Resistivity Probes	43
8.3-7	F versus ϕ Plot for Sandstones	44
8.3-8	Acoustic Velocity Logging	45
8.3-9	Acoustic Televiewer Diagram	46
8.3-10	Example of Acoustic Televiewer Image	47
8.3-11	Example of Cross-plot of Acoustic Velocity and Neutron Logs with Geologic Interpretation	48
8.3-12	API Gamma Ray Units for Various Tertiary Sediments	49
8.3-13	Tube Waves Generated by Seismic Energy Incident on Permeable Fracture Zones	50
8.3-14	VSP to Determine 3D Geometry of Strata, Moduli Values and Hydraulic Conductivity	51
8.3-15	Relationship Between Hydraulic Conductivity and Ratios of Tube Wave to P Wave Amplitudes as a Function of Frequency	52

SECTION 8.3
BOREHOLE GEOPHYSICS

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page No.</u>
8.3-1	Common Borehole Logging Techniques	54
8.3-2	Compressional and Shear Velocities in Rocks . . .	55

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STANDARD REFERENCES FOR MONITORING WELLS
SECTION 7.0 GROUNDWATER MODELING



SECTION 7.0
GROUNDWATER MODELING

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
7.1	GROUNDWATER MODELING OVERVIEW	1
7.1-1	Introduction	1
7.1-2	Purpose	1
7.1-3	General Applications	2
7.2	MODELING TERMINOLOGY	3
7.2-1	Terminology	3
7.3	MATHEMATICAL MODELS	6
7.3-1	Types of Models	6
7.3-2	Analytical Models	7
7.3-3	Numerical Models	8
7.3-3.1	Finite-Difference Technique	11
7.3-3.2	Finite-Element Technique	11
7.3-4	Solute Transport Models	12
7.3-5	Application of Numerical Models to Groundwater Flow Problems	14
7.3-6	Modeling Limitations	14
7.4	PROCEDURES FOR CONSTRUCTING A NUMERICAL FLOW MODEL	16
7.4-1	Modeling Team	16
7.4-2	Conceptual Model	17
7.4-3	Selection of an Appropriate Model	19
7.4-4	Data Compilation	20
7.4-4.1	Geometry of the Aquifer System	21
7.4-4.2	Transmissivity	22
7.4-4.3	Storage Coefficients	23
7.4-4.4	Identification of Surface Water Features	23
7.4-4.5	Leakage	23
7.4-4.6	Delineation of Discharge and Recharge Areas	23

SECTION 7.0
GROUNDWATER MODELING

TABLE OF CONTENTS (continued)

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
7.4-4.7	Piezometric Heads	24
7.4-5	Definition of Boundary and Initial Conditions	24
7.4-6	Construction of the Model Grid	25
7.4-7	Assignment of Parameters to Nodes	26
7.5	PROCEDURES FOR RUNNING A NUMERICAL FLOW MODEL	27
7.5-1	Model Calibration	27
7.5-2	Model Validation	28
7.5-3	Sensitivity Analysis	28
7.5-4	Forecasting	29
7.6	REPORTING MODEL RESULTS	30
7.6-1	Presentation of Results	30
7.6-2	Purpose	30
7.6-3	Conceptual Model	30
7.6-4	Data Collection	30
7.6-5	Model Description	30
7.6-6	Assignment of Model Parameters	31
7.6-7	Model Calibration	31
7.6-8	Model Validation	31
7.6-9	Sensitivity Analysis	31
7.6-10	Data Preprocessing and Postprocessing	32
7.6-11	Model Prediction	32
7.6-12	Model Results	32
7.6-13	Model Records	32
REFERENCES	33

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page No.</u>
7-1	Finite Difference and Finite Element Representations of an Aquifer Region	35
	a. Map View of Aquifer Showing Well Field, Observation Wells, and Boundaries	
	b. Finite difference Grid with Block-Centered Nodes, Where Δx is the Spacing in the x direction, Δy is the Spacing in the y Direction, and b is the Aquifer Thickness	
	c. Finite difference Grid with Mesh-Centered Nodes	
	d. Finite element Mesh with Triangular Elements, Where b is the Aquifer Thickness .	
7-2	Flow Chart to Determine if Modeling is Required	36

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page No.</u>
7-1	Natural Processes that Affect Subsurface Contaminant Transport	37

7.1 GROUNDWATER MODELING OVERVIEW

7.1-1 Introduction

Groundwater flow/solute transport models are tools designed to provide the user with greater understanding of, and the ability to quantify, groundwater flow and solute transport in an aquifer system. Groundwater models have been used for many years to simulate groundwater flow and are the basis for predicting solute transport in aquifers. The goal of groundwater modeling is to integrate the existing knowledge about an aquifer system such that it tests the conceptual model of the system (i.e., hypothesis testing). This is accomplished by predicting the value of an unknown variable (e.g., piezometric head or solute concentration at various points in an aquifer) given a specified set of initial and boundary conditions. Models are also used to determine flow to wells, flow to and from streams, heat transport in groundwater, regional flow patterns, flownet analyses, and production well design (Walton, 1985).

Mathematical models have gained wide acceptance in the groundwater field. This Standard Reference describes the basic differences between analytical and numerical models, outlines the principal steps in the construction of numerical groundwater flow and solute transport models, and provides recommended quality control procedures for modeling.

This section of the Standard References has been prepared in response to numerous requests for inclusion of some material about groundwater modeling. It represents an attempt by DEP to provide an overview of the subject. It does not represent an endorsement by DEP of any particular type of approach, but will discuss the appropriateness of using (or not using) a numerical rather than an analytical model in reports submitted to the department. It is outside the scope of this section to undertake an in-depth discussion of modeling techniques. Good documentation is a critical and often overlooked element in modeling. It is essential that, throughout the entire process, the modeler documents all steps performed, from the initial conceptual model through the various simulations to the final product.

7.1-2 Purpose

The purpose of a groundwater flow model is to be able to make predictions or gain insight into an aquifer system by creating, via mathematical expressions and equations, a simulation of the distribution of piezometric head in an aquifer. This simulated data set of piezometric heads represents values that have been measured at specific locations (i.e., monitoring wells, piezometers, staff gages). Once a model has been created and properly calibrated (i.e., a process of comparing simulated vs. measured heads and adjusting the model parameters accordingly), the model can be used to forecast what the distribution of head might be for a different set of pumping, recharge or aquifer conditions.

7.1.3 General Applications

There are many applications for groundwater flow models. It might be important, for example, to know what the resulting water table might look like if a cutoff wall or french drain were installed in the aquifer, or what the influence of a lagoon or impoundment would have on the flow field, or what the capture zone of a recovery well might be for different pumping rates. Larger scale applications include defining a well head protection area for a municipal water supply or predicting the geometry of a contaminant plume.

One word of caution is offered to the reader: models do not necessarily provide unique solutions when groundwater flow or contaminant transport are being modeled, since combinations of different hydrogeologic and contaminant transport parameters can produce similar results. Groundwater modeling is not an easy task. At a minimum, an in-depth understanding of groundwater flow is required. A reliable model begins with collection of comprehensive data on the aquifer being studied and ends with calibration to a wide distribution of known heads. Care must be taken not to misuse models, which may lead to erroneous conclusions. Misuse of models is more likely to occur if the data base on the aquifer is limited and does not contain significant information with which to compare and verify the response of the model.

In addition, on a larger site, as new field data is acquired, the model can be periodically updated. Thus a "second", or even "third", generation model may be constructed as more monitoring wells are installed, or as the boundary conditions are better understood, or as more water quality information is gathered.

7.2 MODELING TERMINOLOGY

7.2-1 Terminology

There are a few basic terms that must be understood in order to discuss groundwater models:

Advection - Advection is the transport of a non-reactive or conservative solute (i.e., a solute that travels without undergoing reactions with the aquifer matrix) at the average groundwater velocity which is equal, in a homogeneous porous media, to the specific discharge (q) divided by the porosity (n).

Boundary Conditions - Boundary conditions are site-specific physical or hydraulic conditions that describe the flux or piezometric head conditions at the edges of the groundwater system. Physical boundaries are formed by the presence of an impermeable body of rock or significantly lower permeability unit or large body of water while hydraulic boundaries include groundwater divides and streamlines. These boundaries, described as mathematical expressions in the model, have a dominant effect on defining groundwater flow in the aquifer being modeled. Poorly defined boundary conditions will result in a problem that is ill defined and for which no meaningful solution can be obtained. There are three basic types of boundary conditions that are used in constructing numerical flow models:

1. Specified head - The piezometric head is known for surfaces bounding the flow region. Examples include ponds, streams and reservoirs with an unchanging head that is in good hydraulic connection with the aquifer or an equipotential line of known value. As constant heads represent potentially infinite sources or sinks in the model, specification of such boundaries needs to be undertaken with care.
2. Specified flux - The flow rate (i.e., flux) is known across surfaces bounding the region. A leaky till/stratified drift boundary is an example of a specified-flow boundary. A special type of specified flux boundary is a no-flow boundary (an impervious or barrier boundary). Another example of a no-flow boundary is a groundwater divide or a flow line.

Note: Equipotential lines or flow lines may be used as model boundaries as long as they are far enough away from nodes where pumping or recharging centers are located so that the boundaries are not influenced by these stresses.

3. Head-dependent flux - The flux is a function of head at this boundary. This is referred to as a mixed boundary because it relates boundary flux to boundary head. Its most common use is to represent interaction between a water table aquifer and a stream or

river which is separated from the aquifer by a semi-pervious boundary (e.g., a silt bed lining the bottom of a channel).

Dispersion - Dispersion is the process of solute spreading and dilution as advection carries it along. It is the result of mechanical mixing as well as molecular diffusion that occurs as water migrates through a porous medium. In more permeable formation (i.e., sands and gravel) mechanical mixing and advection are the dominant processes by which a solute spreads from a source area. In low permeability formations such as clay or silty clay, molecular diffusion is generally the dominant process by which a solute migrates from a source area. It should be noted that if preferential migration pathways are present in the low permeability material, due to localized lithologic variations or the presence of vertical cracks, then advection and mechanical mixing can play a dominant role as well.

Initial Conditions - Initial conditions are those conditions that exist in the aquifer at time equals zero in the simulation. For example, the elevation of the water table or piezometric head is often specified as an initial condition in transient groundwater flow models or initial concentrations would be specified in the case of a transient solute transport mode. In steady state simulations, the initial conditions may be relatively unimportant, but for transient simulations, the initial conditions are critical.

Model Calibration - Model calibration is the process of comparing computed values (e.g., piezometric head, stream base flow, etc.) that are determined at the end of a model run with actual values of head (i.e., measured in the field) and making adjustments to the nodal parameters or model boundary conditions until there is agreement between the two values. This is not a node-by-node exercise, but generally parameter values are varied over areas of the model to improve overall matching. While heads should match reasonably well, flow directions, hydraulic gradients and overall water balances may be even more important aspects of the calibration matching.

Model Construction - Model construction is the process of using the physical and hydrogeologic data obtained about the aquifer together with the modeler's conceptual model of the system and, by means of employing a model grid, assigning values such as hydraulic conductivity, transmissivity and storativity to each node. The boundary conditions and initial conditions are also specified during model construction as required by the conceptual model.

Model Grid - The model grid is a two or three dimensional representation of the aquifer geometry. The model grid consists of connected quadrilaterals or triangles that resembles a screen mesh. Figure 7-1 depicts an aquifer and examples of what some two dimensional model grids might look like for finite difference or finite element model applications.

Model Simulation - A model simulation refers to the computer generating a set of piezometric heads.

Model Verification - Model verification is performed once the model is calibrated. The procedure for verifying a model is accomplished by running the model for a different set of conditions, and correspondingly a different set of measured heads, than the set that was used to calibrate the model. If the model is able to compute a set of heads for the second set of conditions that matches the field measured heads for those conditions, then the model is considered to be "verified" and "well calibrated". Care should still be exercised, however, when running the model under conditions much different than observed or calibrated.

Node - A node represents the physical position in the aquifer where the average hydrogeologic properties are defined and piezometric heads are calculated. In some models, the nodes are the centers of the grids (see Figure 7-1(b)) while in others they are the intersections of the grids (see Figure 7-1(c) and (d)). In a block centered grid, aquifer properties and hydraulic stresses are typically assigned to the block surrounding the node. In a mesh centered grid, properties are assigned to the area surrounding the node. Infinite element models, aquifer properties can either be assigned to the node or the element (Anderson and Woessner, 1992). The head at the node represents the average head for the area immediately adjacent to the node.

Solute Transport - Solute transport in groundwater is the migration of compounds in solution through a saturated, porous medium. Processes such as advection and dispersion are two of the dominant mechanisms which govern this process. A contaminant may be subject to other mechanisms such as retardation, chemical or biologic transformation, or volatilization which will reduce anticipated concentrations. A solute which does not degrade is said to be conservative.

Steady State - Steady state refers to an equilibrium condition whereby over long periods of time, hydrogeologic systems may achieve or approximate some non-changing conditions in which heads or concentrations do not change with further passage of time. Such systems are said to have achieved steady state. Models may deal with this in different ways. Some have "steady state" options, while others require the user to specify some long period of time and/or closure criterion beyond which changes in head are considered inconsequential.

Transient - Transient refers to a non-equilibrium condition whereby a model is allowed to run for a specified period of simulated time. Typically, initial conditions are steady state in order to correctly interpret head changes under transient conditions, due to stresses in the model, e.g., pumping.

7.3 MATHEMATICAL MODELS

While the earlier subsections of Section 7.3 are written primarily referencing flow modeling, the techniques and concepts apply equally to solute transport models. Section 7.3-4 discusses added considerations specific to solute transport.

7.3-1 Types of Models

A mathematical model is a set of equations that describes the physics of a system or process. Mathematical groundwater flow models are powerful tools for studying cause-and-effect relationships within groundwater systems. However, unlike physical or analog models, mathematical models provide varying degrees of tangible representation of the system that is being simulated. The types of mathematical models are stochastic or deterministic while solution techniques may be analytical or numerical.

Application of a stochastic model attempts to recognize that parameters do not have a single value over the domain of the aquifer. Instead, a parameter is likely to have a certain probability distribution, even for a relatively homogeneous material. Stochastic models attempt to account for this variance in the basic parameters by determining or assuming a probability distribution function (pdf) for some model input parameters. For example, hydraulic conductivity generally has a log-normal distribution, while other parameters may have normal distributions. The stochastic model (for example, the Monte Carlo method) randomly samples from the input parameter distribution and calculates a result. After a large number of iterations, possibly hundreds, enough data points are accumulated to identify a probability distribution for the output parameter. Initial data requirements can be large (to adequately determine the input variable distributions) and computer run time can be high (to provide the number of runs required to determine the output pdf). Stochastic models are rarely used except for very simple flow model situations.

Analytical models are equations which are the closed form solutions to the governing equations for flow and transport with appropriate boundary and initial conditions. In order to obtain the closed form solution, it is often necessary to assume a simplified aquifer condition, simple boundary conditions, and single values (no spatial distribution) for the input parameters. Depending on the situation, an analytical model may or may not be a good choice for accurately determining output parameter values for a specific site. However, it may be possible to select conservative values for the parameters and construct a worst-case scenario. If this approach provides satisfactory results, more detailed (i.e., numerical) modeling may not be necessary. Analytical models are generally used for simple systems and for screening types of analyses.

Numerical models employ a variety of numerical approximation methods to represent the partial differential equations that govern flow and transport. These include finite difference methods that use algebraic approximations, finite element methods that use minimization of residuals of weighting functions integrated over the model domain (Galerkin method), or approximations of equation forms over typical conditions of groundwater flow, such as the method of characteristics. Examples of numerical models using these various approaches are MODFLOW, AQUIFEM, and MOC, respectively. These approximations are applied over each model element or node, giving rise to a set of simultaneous equations that may then be either directly solved by matrix inversion methods, or, more typically, by iterative procedures that are more efficient than the matrix methods when large arrays are involved. Data requirements and levels of effort are generally much greater for numerical models than for analytical models.

The basic difference between analytical and numerical models is the degree of simplification that is assumed for the boundary conditions and physical system being modeled. The choice between selecting an analytical model or a numerical model may be a function of the goals of the modeling, available time and budget, and the quantity and quality of data for the site. Some modelers, however, will construct preliminary models with very little data and use the model as an aid to developing the field program. Often an analytical model, calculated for limiting (maximum or minimum expected) values of parameters, may provide a satisfactory basis for a decision (e.g., quantifying the volumetric rate of flow of groundwater into a recovery trench), and thus save the considerable expense and time required for a numerical model. In any case, a good conceptualization of the aquifer system is required in order to evaluate the applicability of any given model, and to appropriately include consideration of the underlying assumptions of that model.

7.3-2 Analytical Models

Analytical models frequently assume a substantial simplification of the groundwater system, but they provide exact solutions to the mathematical expression. In analytical models, the flow is most often described as occurring in confined aquifers that are assumed to be:

- homogeneous and isotropic;
- infinite in areal extent;
- uniform thickness throughout;
- groundwater temperature, density, and viscosity are assumed to be constant;

- production and injection wells have infinitesimal diameters and no storage capacity or finite diameters with specified storage capacity;
- except for flowing wells, areal discharge and recharge to the aquifer are constant (and might not be included); and
- hydrogeologic boundaries usually are not addressed in the general solution. However, boundary problems may be handled by using image well theory (Walton, 1985).

Darcy's law, one form of which is given by the expression:

$$q = KJ$$

where:

q = specific discharge;

K = hydraulic conductivity; and

J = hydraulic gradient

is an equation of motion that reflects the most simple analytical model. Using it requires satisfying all of the conditions previously stated. If the hydraulic conductivity and hydraulic gradient are known, then the specific discharge can be quantified. Furthermore, given any two of the three parameters, the third variable can be calculated at any other location in an aquifer that has homogeneous, isotropic properties.

Other examples of analytical models include the Dupuit-Forcheimer discharge formula for flow in unconfined aquifers and Jacob's approximation of the Theis equation for predicting the transient drawdown response due to the influence of a pumping well. Some texts containing these and other analytical models include: "Hydraulics of Groundwater" (Bear, 1979), "Quantitative Hydrogeology" (deMarsily, 1986).

7.3-3 Numerical Models

Numerical models represent the equation of motion and statement of mass conservation of groundwater in an aquifer system. They rely on the same principles and equations as analytical models, but they generally require fewer simplifying assumptions. The theoretical basis for the governing groundwater flow equations is well documented and is based on a combination of Darcy's Law and the groundwater mass balance equation (Wang and Anderson, 1982; Mercer and Faust, 1981). Some of the principle input parameters necessary to construct a groundwater flow model at a specific site must be identified. These parameters include:

- the shape of the potentiometric surface for confined aquifers or the piezometric surface (i.e., the water table) for unconfined aquifers;

- the distribution of hydraulic conductivity, and depth to bedrock or transmissivity in the aquifer;
- the geometry of the aquifer; and
- the location and nature of recharge or barrier boundaries.

The potentiometric head (needed for model calibration) can be measured at selected locations in the field; transmissivity or hydraulic conductivity and depth to bedrock can be estimated with reasonable reliability using pumping or, if necessary, slug test data, boring log information, or a host of other field or lab tests. (see Section 7.4-4.2 for greater elaboration); and the aquifer/aquitard geometry can be determined from boring log and pumping test information, surface geophysics and survey data. Geophysical techniques such as seismic refraction, electrical resistivity and ground penetrating radar are cost effective ways of characterizing aquifer geometry, stratigraphy and, to some degree, the depth to the water table.

The acquisition of this physical data, in conjunction with water quality results, is invariably limited in extent, principally because of economic considerations. It is, however, the primary and fundamental source of information upon which the model is constructed. Consequently, the inherent weakness associated with many modeling efforts is lack of sufficient data of usable quality. It behooves the project manager and modeler to continually be aware of this when conceptualizing and constructing models. It is also why the calibration procedure and sensitivity analysis are such an important part of the modeling process.

The discharge/recharge relationship of surface bodies of water (i.e., lakes, ponds and streams) within and adjacent to the aquifer needs to be identified in order to properly construct and calibrate the model. This data can be obtained by taking contemporaneous stream flow measurements at different locations in a stream or river during extended periods of little or no rainfall (three or four days) or by utilizing streamflow measurements at USGS gauging stations. The water that is in the stream channel during these times is referred to as base flow and represents almost entirely the groundwater portion of stream flow. Using a technique referred to as stream tube or flow net analysis, this information coupled with piezometric head data in the aquifer can be used to estimate the hydraulic conductivity in other parts of the aquifer. At the very least, this information will be needed to calibrate the model when the nodal water mass balance (i.e., the amount of water coming in and out of each node) is performed. Seepage meters may also be used to quantify flux between the aquifer and a surface water body. When used with piezometers below the streambed, hydraulic conductivity of the streambed can be estimated (Lee, 1978).

Gathering physical and chemical data for an aquifer is generally very costly and time consuming given:

- the geologic variability that exists in glaciated terrains such as New England; and
- the types and required detection limits of the contaminants that are being regulated.

That is why it is very important that the project manager, field geologist and modeler all have a good conceptual understanding of the hydrogeology of the aquifer. If the team lacks or is weak in any of these areas:

- a firm theoretical understanding of flow through a porous or fractured bedrock medium;
- the nature and characteristics of the contaminants in question;
- the influence that any production wells may have on regional flow;
- how the aquifer is bounded; and
- appropriate protocols for installing and sampling monitoring wells and conducting other field activities,

then the following will occur:

- a poorly defined conceptual model;
- the design and execution of an inadequate field sampling program;
- insufficient and/or inaccurate data with which to construct and calibrate a groundwater flow and, if appropriate, a solute transport model; and
- a poorly designed remedial strategy.

In most numerical models, the governing partial differential equations are approximated by algebraic difference expressions relating unknown variables (e.g., head, flux) at discrete points (nodes) at different times (Javandel et al., 1984). Consequently, more complex conditions such as heterogeneity and anisotropy can be more accurately simulated in numerical models than in analytical models. Typically, numerical models utilize more data than analytical models because varying aquifer properties may be described at numerous, discrete points within an aquifer. Complex or

irregularly shaped boundaries such as leaky streams or impervious (i.e., no-flow) boundaries or a meandering river are generally easier to model using a numerical approach, while analytical models are severely constrained in this regard.

7.3-3.1 Finite-difference Technique

There are two common types of numerical techniques that are applied to groundwater problems: finite-difference and finite-element methods. Finite difference techniques solve the groundwater-flow equation by approximating the derivatives of partial differential equations at regularly or variably spaced points in the system. The finite-difference technique employs a grid of squares or rectangles as depicted in Figures 7-1(b) and (c). Figure 7-1(b) is a block centered representation of the aquifer shown in Figure 7-1(a), while Figure 7-1(c) is a mesh or node centered grid of the same aquifer. There is no significant difference between the two. If there are lateral variations in hydraulic properties within the aquifer, such as transmissivity or storativity that are linear in nature, use of a block centered grid makes it slightly easier to delineate and assign values to those regions.

Notice that in either case, (b) or (c), because of the perpendicular nature of the intersecting grid lines, some of the grid is either outside or inside the physical aquifer boundary. Since aquifer geometry and boundaries are rarely linear features, this condition will invariably arise. The only time that it may present a problem is if accurate piezometric data are desired adjacent to those features. If that is the case, then a finer grid size will result in a more accurate determination of piezometer head. However, a finer mesh will increase the number of nodes necessary to describe the feature which in turn will result in greater computation time. This generally translates into an increased level of effort and expense in model construction and validation and computing costs.

7.3-3.2 Finite Element Technique

If the geometry or internal physical features are curvilinear, then it might be easier to model the aquifer using a finite element approach with triangular elements of varying size as depicted in Figure 7-1(d). Irregular aquifer or lateral internal variations in geologic properties (e.g., lateral changes in aquifer properties or irregularly shaped water bodies) can be more readily accommodated with a finite element mesh although the time necessary to construct the grid and input the data into the computer can be considerable.

The finite-element method approximates differential equations by an integral method. The model area is divided into sub-regions, or elements, and the finite-element model grid may consist of triangles or

quadrilaterals. Numerical models utilize a variety of solution techniques to solve the resulting equations. Additional information on finite-difference and finite-element techniques and solution techniques is contained in numerous introductory modeling texts (e.g., Wang and Anderson, 1982; Walton, 1985).

7.3-4 Solute-Transport Models

Solute-transport models simulate the distribution of contamination as concentrations (i.e., mass per unit volume of a compound) in an aquifer by simultaneously solving both the flow equation and the transport equation. Physical, chemical, and biological processes all affect the rate and migration of contaminants in an aquifer.

Solute transport processes include physical phenomena, and chemical and biological reactions. Individual processes are, in some cases, fairly well understood under laboratory conditions and can be somewhat replicated under field conditions in saturated porous media. Solute transport in fractured bedrock is much more difficult to identify and characterize because of the heterogeneous anisotropic nature of the aquifer. In addition, when multiple contaminants are present that respond differently to different processes in either media (unconsolidated or bedrock), the resulting synergistic reactions become difficult to model. Thus, real problems arise in very heterogeneous or fracture-dominated systems or when nonaqueous phase contaminants or solutes that react with solid, liquid or biological components of the subsurface are present. These cases, and they are common (i.e., gasoline spills, metals, organic solvents, etc.), can be very difficult to model. Consequently, this greatly limits the reliability of using mathematical models of solute transport to predict future site conditions for such situations.

The basis for the selection of values of various input parameters for solute transport models, such as dispersion coefficients, is still being debated. Another required input parameter which is generally not well defined is the strength of the contaminant source. Also, input parameters for the transport equation, such as dispersion coefficients and biotransformation rates, are difficult to quantify in the field with available technology, particularly in groundwater regimes where flow is very slow.

Assessment of solute transport requires a multi-disciplinary approach that integrates the geologic, hydrologic, chemical, and biologic processes and features that are important at a site (Keely, 1987). A complex array of chemical wastes and a poorly documented contaminant release history are associated with most contaminated sites, thus making solute-transport modeling a difficult proposition. Some of the known factors that influence the fate and transport of contaminants are listed on Table 7-1. At the present time, there are many gaps in our understanding of solute-

transport phenomena and the appropriate methods for characterizing them.

Of the physical processes affecting solute transport, advection, a flow dominated process, is the most well understood parameter. Recent studies (Sudicky, 1986) indicate that advection may be the dominant control in the physical processes of solute transport and that the delineation of the complex and difficult-to-measure parameters such as dispersion or diffusion may be unnecessary. These studies suggest that a detailed description of the distribution of hydraulic conductivity in an aquifer may be the most important factor in simulating solute-transport, although obtaining this data could be economically prohibitive. Hence, in order to predict contaminant transport adequately, it is imperative to have a well-calibrated groundwater flow model. Other researchers, however, suggest that calculations of travel time based solely on advection and longitudinal mechanical dispersion may greatly underestimate breakthrough of the solute (Keely, 1987). Finally, under certain circumstances, for example, when flow velocities are extremely low (e.g., when leachate passes through clay liners), molecular diffusion becomes the controlling component for solute transport, unless there are conduits for vertical flow through the clay liners such as cracks, roots, etc...

The measurement and mathematical description of chemical processes in the subsurface are less certain than the physical processes affecting solute transport. Although parameters such as ion exchange and oxidation-reduction reactions are well understood in the laboratory, their application to field conditions is difficult. In addition, the complex interaction of various organic and inorganic compounds that are often present at contaminated sites is difficult. The solute-transport models currently available do not take these chemical and geochemical interactions into account.

Biological processes are another set of frequently overlooked parameters that affect the fate and transport of contaminants. These processes include the biotransformation of one compound into another as the result of subsurface biological activities. Although the presence of these processes is recognized, the factors influencing the rates, abundance, and impact of these processes are not well-defined. The effect of biological processes on solute fate and transport is currently an area of intensive research and, as these processes are better quantified in the field, they may be able to be more accurately modeled.

Due to the complex nature of the interactions of these processes, it is often necessary to make assumptions and simplifications to obtain mathematically manageable solutions (Keely, 1987). In many cases, the impact of certain parameters must be ignored completely in order to describe the problem mathematically. The magnitude of errors arising from these assumptions and simplifications must be carefully evaluated. For example, transport models, which only consider advection and

dispersion, are not likely to be representative of a case where contaminants may be removed by a process such as adsorption. Consequently, the accuracy and applicability of solute-transport model simulations must be reviewed in light of the assumptions made during the modeling phase. Until there is a better understanding of all the subsurface processes affecting solute transport, the results simulated by solute-transport models should be applied with caution when making remedial and/or regulatory decisions with regards to a site. Use of conservative values for transport parameters can, however, establish reasonable limits to expected concentrations. Under worst-case conditions, it may be possible to establish acceptable risk criteria for a site.

7.3-5 Application of Numerical Models to Groundwater Flow Problems

Numerical models can be applied to a variety of groundwater problems to increase the user's understanding of the natural flow system and how the flow system might respond to various stresses, both natural and man-made. Models can be used either for interpretive or predictive purposes to simulate how a particular aquifer may respond to recharge, pumping wells, or some other form of hydraulic remedial action. Models can also be useful tools for designing a subsurface monitoring program for site investigations or long-term monitoring. Typical applications of numerical models include:

- Testing and improving the conceptual model of a ground water flow system initially formulated on the basis of field observations;
- Evaluation of the impact of various activities on groundwater quantity (aquifer stress and yield);
- Evaluation of the effectiveness of alternative remedial pumping schemes;
- Evaluation for risk assessment purposes of the potential exposure of receptors to various contaminants over time;
- Definition of well head protection zones;
- Evaluation of saltwater intrusion; and
- Design of monitoring well networks.

7.3-6 Modeling Limitations

An important step in any modeling program is to determine if the construction of a mathematical model is appropriate and necessary. Figure

7-2 is a flow chart for determining whether or not modeling is required. Often times, gathering additional data will improve the conceptual understanding of the site; however, a cost benefit analysis that considers the goals of the investigation should be performed prior to collecting more data.

In some cases, models are used to predict current groundwaer contaminant concentrations at potential exposure points, utilizing only data near the contaminant source. Project managers should constantly evaluate whether simply gathering real, current data at the potential exposure points is useful and beneficial.

Because of the sometimes extreme heterogeneity of the geologic environment or the potential for different interpretations of the same hydrogeological data set, a good modeler should always take a conservative approach in evaluating the validity of the model in its ability to estimate some prior or future condition. Embarrassing stories abound in modeling circles concerning the discovery of previously unidentified geologic features identified with subsequent drilling programs which, by their presence, necessitated major revisions to the conceptual and numerical model. Models aid in understanding how a system works, but room for refinement of that understanding always exists.

7.4 PROCEDURES FOR CONSTRUCTING A NUMERICAL FLOW MODEL

7.4-1 Modeling Team

At a minimum, the modeling team should consist of the modeler and the site geologist/hydrogeologist or engineer skilled in groundwater hydrology. The site project manager need not be a geologist/hydrogeologist. The modeler should conduct one or more site visits and frequently discuss the model with the site geologist/hydrogeologist with regards to where he/she feels the weaknesses of the model exist and what kind of information he/she needs to strengthen the model. Under no circumstance should the modeler construct the model without consulting with the site geologist/hydrogeologist, unless he/she is also the site geologist/hydrogeologist or has conducted the field work.

The model selected for use on a project should vary according to site conditions and modeling requirements. The level of experience of the modeler should also vary with the more experienced modelers constructing the more complex models. Depending upon the size and complexity of the model and staff availability, a less experienced modeler should serve as an aid to the principal modeler assisting in grid construction, data entry and performing the computer runs. In this way he/she gains more experience in learning how to construct and calibrate more complex models.

If a solute transport model is also required, then depending upon the contamination that is being modeled, a chemist in the particular branch of chemistry in question should be part of the modeling team. That individual should review the geologic and chemical data and participate in the development of the conceptual model. The types of contaminants that can be modeled include:

- inorganics (including metals);
- volatile organic compounds;
- acid/base neutral compounds;
- dense or light non-aqueous phase liquids (DNAPL or LNAPL, respectively); and
- radioactive compounds.

All of these classes of compounds have different physical, chemical and biological properties and will behave and react differently in the aquifer and in some cases with each other as well. For some chemicals (e.g., for a DNAPL plume) and/or some aquifer conditions (i.e., fractured bedrock) acquiring sufficient data could be extremely difficult.

Another important requirement for a modeling program is time. Where analytical models may take an hour or a day to set up and evaluate, numerical models, depending upon their size and complexity, may require weeks or months to properly design and calibrate.

7.4-2 Conceptual Model

The conceptual model is the modeler's and project geologist/hydrogeologist's concept of how the physical hydrogeological system works. It includes a discussion of all of the controlling factors in the system, such as aquifer extent and thickness, sources, sinks, and hydrogeologic boundaries. Alternatively, it may be a working hypothesis that the modeler wishes to test. In addition, the conceptual model becomes the basis for developing future data gathering efforts. Any model is only as good as the conceptual model and its ability to capture the essential elements of the hydrogeologic system.

A conceptual model should be developed whenever a site is being evaluated irrespective of whether or not a model is to be constructed. It is a "picture" in the project manager's mind of what the site subsurface and groundwater flow conditions are. It is, or should be, continually refined as new data are acquired. The development of a conceptual model should begin as the first pieces of information are received. Activities as rudimentary as review of a topographic map, hydrologic atlas or conducting a site visit should begin to stimulate ideas or "concepts" about the site hydrogeology. As more data is gathered and reviewed (e.g., aerial photographs, boring logs, prior reports, etc.), the site geologist/hydrogeologist should continually be refining his/her mental image of the aquifer. The evolution of the conceptual model is the primary responsibility of the site geologist/hydrogeologist not the modeler. The site geologist/hydrogeologist synthesizes all of the data and presents the conceptual model to the modeler for review and discussion. The modeler then reviews the conceptual model and depending upon the goals the modeling effort may have some specific data needs or requirements in order to fulfill those goals. The subsequent field work initiated for the project should, costs permitting, attempt to fulfill those goals.

Very often contamination exists at the site (i.e., a leaking UST, a lagoon, a waste pile). A conceptual model of the waste source and its migration pathway(s) to the subsurface also needs to be developed simultaneously and integrated with the conceptual flow model. This should be done irrespective of whether or not a solute transport model is to be constructed as it will aid in locating monitoring wells or sampling locations.

Whatever the type of model to be constructed or used (i.e., analytical or numerical), a conceptual model of the aquifer needs to be created. As

dictated by the site complexity and level of effort requested by the private party or DEP and the goal of the modeling effort, the conceptual models should include, but not be limited to:

- sketches;
- cross-sections;
- block diagrams;
- flow nets in map view and in cross-section;
- aquifer geometry;
- distribution of geologic materials both laterally and vertically;
- nature of the underlying bedrock;
- description of lateral aquifer boundaries (i.e., valley walls, streams, etc.);
- a discussion of major withdrawals or recharge to the aquifer;
- leakage from overlying bodies of water;
- wetlands or underlying aquifers;
- the nature of any confining units that might be present;
- the gaining or losing nature of any streams or rivers within or adjacent to the aquifer;
- horizontal and vertical hydraulic gradients;
- hydraulic conductivity and storativity of the different geologic materials in the aquifer; and
- the distribution of natural recharge across the aquifer.

In general, the more complex the site, the greater the level of effort is required to evaluate its hydrogeology and the more detailed is the conceptual model with fewer simplifying assumptions. Conversely, a simple site requires a lower level of effort and results in a less detailed conceptual model. Modelers should not extend a limited data set in order to achieve results for a complex set of goals.

7.4-3

Selection of an Appropriate Model

The selection of the type of model should be based on the objectives of the program, the complexity of the system, and the available data. According to de Marsily (1986), situations where the construction of a numerical model may be more suitable than an analytical model include:

- needing to identify migration pathways and predict end point receptor concentrations;
- having boundary conditions (either flow or no-flow) with complex shapes and/or situations where assuming infinite areal extent, constant aquifer thickness, and homogeneous, isotropic conditions or the use of image wells cannot adequately describe the system;
- having a non-linear problem where no analytical solution is available.
- varying aquifer geometry that is too intricate to be adequately represented with an analytical model, i.e. single values of hydrogeological parameters selected for the analytical model are inadequate for describing the real system; and/or
- having an analytical solution available, but which is very time-consuming or complex to calculate.

Selection of the most appropriate numerical model should be based on site conditions, the purpose of the modeling exercise, and the availability of data to adequately construct and calibrate the model. For example, a two-dimensional (2-D) groundwater flow model is appropriate if groundwater flow can reasonably be assumed to be horizontal. In constructing a 2-D model, if vertical heterogeneities exist in the aquifer, vertically averaged values of hydraulic conductivity can be calculated and used as input data. A cross-sectional or profile model can be constructed when consideration of vertical flow is important. The profile, however, needs to be constructed along a flow line.

A three-dimensional (3-D) model is appropriate if flow or solute transport in the third dimension is important to the understanding of the site hydrogeology (e.g., during pumping simulations in the vicinity of the pumping well, or where leaky aquitards are present, where the vertical distribution of head is of major interest, or where significant vertical heterogeneities exist). Three-dimensional models are also very useful in areas where groundwater flow is controlled by topography which may give rise to the presence of local, intermediate and regional flow systems resulting in complex vertical flow conditions.

For any numerical modeling effort, however, there must be sufficient data collected to support its construction, calibration and validation.

Obviously, when constructing a three-dimensional model, the data requirements are significantly greater than for a two-dimensional model. For example, a number of well nests or well clusters are necessary in order to calibrate a 3-D model which greatly increases the cost of the field effort and the length of time necessary to complete it.

When aquifers that have vertical variations in composition and/or have vertical differences in hydraulic head or situations where it is important to know the vertical distribution of head are going to be modeled three dimensionally, multi-level or multi-port wells need to be installed in areas where vertical changes in head are anticipated. Not only is this an expensive and time consuming process, but constructing, calibrating and verifying a three dimensional model becomes very time consuming and expensive as well. For these situations, there has to be an extensive amount of field work of sufficient adequacy to achieve the desired objective.

What constitutes a "sufficient" data set is a matter of interest that deserves some discussion. Geostatistical software packages are available that are used for parameter estimation. "Kriging" is just one of a handful of techniques that is used to take a known data set and interpolate between those values as well as assign a confidence interval for the estimates that have been calculated. Another way of kriging data is to evaluate the data set of a number of values from one well (e.g., water quality) to arrive at a value that is representative of the entire set. Another way of stating the above is that kriging is the process of finding the best linear unbiased estimate at a point (or the average over an area) by linear interpolation from the variable data (DeMarsily, 1986).

The confidence interval of the estimate will vary depending partly upon the number of samples. The data sets for hydrogeologic investigations for the most part are rather limited. Consequently, the estimated confidence interval needs to be looked at carefully. For example, interpolation of a water table data set for an unconfined aquifer (i.e., a water table map) and a map showing the areal distribution of hydraulic conductivity might have similar confidence intervals. However, given the nature of the two parameters, hydraulic head (which spatially varies fairly uniformly and is rather damped) and hydraulic conductivity (which may be randomly distributed), the contoured map of piezometric data is less likely to significantly change with the acquisition of new data than the hydraulic conductivity map.

7.4-4 Data Compilation

A significant amount of data is needed to construct an accurate numerical model. Typically, a model begins with the construction of a series of

maps and stratigraphic cross-sections that describe the aquifer conditions. This information is generally compiled by members of the field investigation team or modeling team and has as its basis the conceptual model that has been developed for the site. Because the conceptual model evolves continually, it is not unusual for the conceptual model to be refined as the data is compiled and depicted in the various types of maps and figures that hydrogeologically describe the site. Input data for a numerical model usually consist of, at a minimum, the items described below.

7.4-4.1 Geometry of the Aquifer System

The geometry of the aquifer system consists of a physical description of the aquifer including the geologic units, their vertical thicknesses and lateral extent. This information is obtained from subsurface borings, surface and borehole geophysical data, surficial mapping, an understanding of the geomorphology and depositional environment, and the construction of geologic cross-sections.

A minimum number of contoured maps should be developed prior to model construction. For a water table aquifer, they are:

- a hydraulic conductivity map;
- an aquifer bottom elevation map (this may or may not be equivalent to a bedrock topographic map);
- a land surface topographic map;
- a map of the elevation of water table; and
- a porosity map, if solute transport is being modeled.

For a confined aquifer, maps depicting the lateral distribution of transmissivity (rather than hydraulic conductivity) in the aquifer and the potentiometric surface are required. In some cases (e.g., transient flow modeling), maps depicting the distribution of specific yield (water table aquifer) or storativity (confined aquifer) may be required. This latter information is generally difficult or expensive to obtain in the field and globally assumed values from published literature are often used in the model. However, depending upon the types of geologic materials present, it may be desirable to use different published values in different parts of the aquifer (e.g., till upland adjacent to stratified drift).

It is not unusual for modelers to use equations for confined aquifers to estimate responses in unconfined aquifers (i.e., holding transmissivity constant), particularly if the dewatering effects in the area of concern are minimal. (Note: dewatering lowers the water table and reduces the

saturated thickness which in turn results in a lower transmissivity.) The advantage to doing this is that data compilation and entry time are significantly reduced. This approach is more acceptable in regions that are distant from a pumping or recharge well or where seasonal changes in the water table are small. The model will accurately reflect head values in those areas. Where dewatering is significant (greater than approximately 10% of the saturated thickness), this approach is not recommended and should not be used without correcting the drawdown for the dewatering effect.

7.4-4.2 Transmissivity

The transmissivity of the aquifer can be obtained directly from pumping tests as well as from other methods. In order of preference, they are:

- pumping tests,
- field tests of hydraulic conductivity (i.e., slug tests),
- dividing estimated regional flow by measured hydraulic gradient,
- laboratory permeability tests on the soils,
- grain size analysis, or
- published data.

When hydraulic conductivity (K) is obtained directly (i.e., slug tests, grain size, etc.), the saturated thickness of the aquifer (b) must be estimated so that the transmissivity (T) can be calculated ($T=Kb$).

Pumping tests, particularly large capacity tests, are the preferred way to estimate transmissivity over large regions of the aquifer. Transmissivities derived from pumping tests are less satisfactory for solute transport models where variations in hydraulic conductivity are more important than average conductivities over a large region. Very often in dealing with contaminated sites, pumping tests, prior to the treatment system being operational, are run at much lower volumetric rates to minimize the extraction of contaminated groundwater and consequently impact a smaller region of the aquifer. Slug tests measure the hydraulic conductivity only in the immediate vicinity of the monitoring well and care must be taken in extrapolating those results very far from where the measurements were taken. Regional flow can sometimes be approximated based on estimates of areal recharge and the upgradient recharge area. Using Darcy's Law, this flow can be divided by the measured gradient and flow tube width to approximate transmissivity. Laboratory tests for hydraulic conductivity require physically taking samples of the aquifer

into a soils lab for permeameter testing and/or for sieve analysis (see Section 3.8-1). In doing this, the soil structure (packing) is disturbed which will alter the hydraulic conductivity. In the absence of field data, published tables may provide reasonable estimates of hydraulic conductivity.

7.4-4.3 Storage Coefficients

The storage coefficients and/or specific yields are also necessary input parameters for transient simulations. Storage coefficients can be determined through aquifer tests, and specific yield can be estimated through aquifer or matrix and void space volumetric tests which are performed in the laboratory. If these data are not available, assumed values for these parameters are often used. An order-of-magnitude value is often assumed for the confined storage coefficient. Specific yield or unconfined storage coefficients can be estimated much more closely.

7.4-4.4 Identification of Surface Water Features

The locations of surface water bodies are also necessary for model construction. Locations usually can be obtained from topographic maps or from aerial photos, although more accurate information regarding these features is generally obtained in the field. The hydraulic connection and flux (i.e., leakage, induced infiltration, or groundwater discharge) between these surface water features and the groundwater system will need to be quantified.

7.4-4.5 Leakage

Leakage rates from semi-confining layers, or induced infiltration or leakage from lakes, ponds and streams can be determined by analyzing data from a well-designed aquifer test or estimated from the geologic description of the adjacent units, based on their estimated thickness, permeabilities, and vertical head differences. Seepage meters and streambed piezometers can also be used to quantify flux from an adjacent surface waterbody into or out of an aquifer (Lee et al., 1978).

7.4-4.6 Delineation of Discharge and Recharge Areas

Depending upon the goal of the modeling effort, the location and rate of recharge to the system—through precipitation, infiltration, and/or injection should be determined based on field measurements or estimated from available geologic and climatological data. Zones where groundwater is extracted from the aquifer system through pumping or natural discharge to surface waters should be identified and quantified to the extent possible. Measurement of pumping rates and temporal variations in pumping rates from wells and the use of stream-gaging and seepage meters in streams and swamps can provide data to help quantify these factors.

7.4-4.7 Piezometric Heads

Piezometric head data are required for the construction, calibration, and validation of a model. These data are obtained from water-level measurements made at various locations and depths in the aquifer. This information can be compiled in the form of water-table and piezometric maps or hydrographs for specific wells. The collection of head data over a period of several years may be required to determine long-term (steady-state) conditions in an aquifer. For 3D models, piezometric measurements should be made in all aquifer layers that are being modeled in order to achieve a good calibration.

It is not unusual for a site to be investigated over a period of years with the modeling effort coming in the later part of the project. Consequently, it behooves the project manager to have water levels measured at a minimum on a quarterly basis until the hydrogeology is understood. Once that occurs, semi-annual measurements (preferably in late spring and fall) can be taken. The U.S. Geological Survey (USGS) has a network of long term monitoring wells in the state that are measured on a monthly basis. This data should be used, when appropriate, to supplement site specific data. Techniques for predicting probable high groundwater levels in Massachusetts and on Cape Cod are available from the USGS (Frimpter, 1980 WRI-OFR 80-1205 and Frimpter, 1980 WRI-OFR 80-1008, respectively).

7.4-5 Definition of Boundary and Initial Conditions

In order to solve the partial differential equations that define the flow regime, the nature and location of the hydrologic boundaries need to be determined. This information may be based initially on a conceptual model of the flow system, however, the existence of boundaries must be verified in the field. Models should maximize the use of any field measurements of stream and pond elevations, or discharge and recharge rates, as well as the physical location of aquifer boundaries. When transient conditions are simulated, initial conditions are also required. For example, in a simulation of flow through an unconfined aquifer, the initial piezometric head values are assumed at the node locations within the aquifer. These head values represent the initial conditions for the transient (non-steady state) simulations.

In some cases the natural limits of the aquifer may be extremely far from the area of interest in the model. In this case artificial boundary conditions may be used, such as constant-head (i.e., an equipotential line), constant flux, or no-flow boundaries (i.e., a groundwater flow line). In applying these artificial boundary conditions to the model, it is assumed that these boundaries will not be significantly affected by the simulation. If pumping or recharging wells are influencing these

boundaries, then the model will need to be reconstructed so as to minimize this interference. The appropriateness of these boundary conditions should be checked to determine their influence on long-term predictions of the model (de Marsily, 1984). This can be accomplished by replacing a constant-head boundary with a specified-flux boundary and running the model again. If the differences in the two simulations are insignificant, then the artificial boundary conditions are not significantly affecting the simulation. Note, however, that the model still might not be valid due to failure of other criteria which are discussed in Section 7.6-3, Sensitivity Analysis.

7.4-6 Construction of the Model Grid

Once the conceptual model has been formulated, the model grid can be constructed. This process is often referred to as discretization. The design of the grid will affect the accuracy of the piezometric approximations at specific locations in the model, as well as the amount of time necessary to run the model on a computer.

A general rule of thumb to follow is that if variable grid spacing is to be used, then the node or grid spacing should become smaller whenever there are abrupt changes in: 1) physical properties (e.g., a till-stratified drift contact); or 2) piezometric head (e.g., adjacent to a production or recharge well). Referring to Figure 7-1(a), (c) and (d), the node spacing in the vicinity of the production wells is much closer than along the model boundaries. The closer grid spacing will provide better resolution of piezometric head in those areas. The trade off for having a finer grid spacing is that in doing so, the number of nodes generally increases which results in greater computational time. This may seem insignificant for a two dimensional model, but can become significant for three-dimensional models. This can be compensated to some degree by creating larger grid spacing away from the areas of interest (e.g., near the model boundaries (see Figure 7-1(d))). With regards to node spacing, some finite difference codes recommend that an adjacent node be no more than 1.5 times the distance between the last two nodes.

The following general guidelines (modified after Mercer and Faust, 1981) should be followed when designing a model grid:

1. Place nodes at pumping centers and monitoring/observation wells. In the case of a tubular well field (i.e., a series of small diameter wells manifolds together), a number of wells can be grouped together at one node.
2. Accurately locate model boundaries so that they correspond with real hydrogeologic boundaries. As depicted in Figure 7-1, finite element techniques can approximate curvilinear boundaries and other features better than finite difference techniques. The loss of this kind of

detail is not significant if knowing exact piezometric heads in those areas is not important.

3. Place nodes close together in areas where there are large variations in geologic conditions or anticipated, significant changes in hydraulic head (for example, near pumping or recharging wells). What defines "close" is really a function of the size of area to be modeled, the number of nodes that are available, and the particular solution technique utilized in the code. The larger the area, the greater the node spacing. The limiting factors are either the software (some codes have a 2,500 node limit) or the hardware (available memory capability).
4. Align the axes of the grid along major directions of anisotropy or heterogeneity.

7.4-7 Assignment of Parameters to Nodes

Once the basic data have been compiled and the model grid has been designed, model parameters can be assigned to each node. At this point, the physical aspects of the aquifer are defined for each node in the model by overlaying the model grid over maps of saturated thicknesses, transmissivity, initial conditions, and other features. The properties are assigned to each node of the model and comprise the input files for the model.

Keying the data into the computer on a node by node basis is a time consuming process and incorrect data can often be entered for a node. It is important to check the input data very carefully prior to running the model. It is pointless to attempt to calibrate the model if the input data is in error. Some errors become apparent only when first attempting to run the model, particularly when using a new or unfamiliar model. The user should plan on some initial debugging runs to aid in correcting input data files.

7.5 PROCEDURES FOR RUNNING A NUMERICAL FLOW MODEL

7.5-1 Model Calibration

Calibration of the model consists of running the model and comparing model-simulated heads to a set of field-measured heads and, where applicable, model-simulated rates of groundwater discharge to a set of field-measured rates of groundwater discharge. This is accomplished through a trial-and-error process of varying aquifer parameters (e.g., transmissivity, storativity, recharge, etc.) in different regions of the model (having, of course, some justification for making the changes) until the match between model-simulated and field-measured conditions is considered acceptable. Calibration can be performed to steady state or average head conditions or to transient conditions. Other calibration criteria include a water mass balance, groundwater discharge to streams (i.e., gain or loss), and, if the model is a three dimensional one, vertical and horizontal head distributions in all layers.

There is no text book definition of what constitutes an "acceptable" match between simulated and measured data. Simulated data will rarely exactly match measured data, however, the difference between the two should be minimized. Two methods of comparing simulated to measured data are to calculate the absolute average difference (AAD) or to calculate a standard deviation and root mean square error (RMSE) for all the data. If the standard deviation and the RMSE is small or if the AAD is small, then the calibration is considered acceptable with the following exception.

There will invariably be outliers, that is locations or nodes where the difference between simulated and field data is substantial. If those nodes are in central areas of the model where predicting heads for future scenarios is desired, then the model calibration should not be considered "acceptable". If, however, those nodes are distant from where forecasting information is sought (e.g., a till upland region adjacent to the aquifer), then this difference often times will have little impact on the modeling results.

A word of caution against too finely tuning a model may be justified here. A more generalized model that calibrates reasonably well may be more valid than one in which the RMSE is very small, but its parameters have been very finely tuned in areas where there is no field data to verify that these changes are warranted.

Also, care must be taken when constructing the model using interior constant head nodes. A river or lake that is large enough and in good hydraulic communication with the aquifer may be represented with a series of constant head nodes. However, if a water body is shallow and

susceptible to large fluctuations in water level elevation, constant head nodes may not be the best representation.

A detailed log of the adjustments that have been made to the input data during the calibration process should be maintained. This will provide a record of the modifications made to the original entries and should help to avoid repeating calibration runs. During the calibration phase, the modifications should be checked against the original conceptual model to ensure that the model is still representative of the physical system. It is easy to stray from the original concept of the system during the calibration process.

The reliability of the model is related to the accuracy with which the model simulates field conditions. It is important to keep in mind, however, that just because the model reproduces one set of field conditions does not mean that it is valid. Modification of different sets of parameters can produce similar solutions. Consequently, the calibration of the model must be performed systematically and with a good understanding of the site conditions. For a particular site, given the proper assumptions, additional field data will often improve the accuracy of the model. Many times it is necessary to perform additional field work to fill in data gaps before an accurate model is obtained. The decision to obtain further data must include a careful weighing of benefit to the model (reflecting model goals) and cost and time involved in obtaining the additional data.

7.5-2 Model Validation

Upon conclusion of the calibration process, the model should be run with a different set of initial conditions produced by a different set of stresses than the initial calibration (e.g. high vs. low water table or pumping vs. non-pumping conditions). Because of the non-uniqueness of the solution, the model should be validated with as many sets of initial conditions as may exist prior to using the model for any forecasting. Preferably, data should be collected at periods of seasonally high and low water tables in order to reflect seasonal fluctuations in recharge and surface and groundwater conditions. Confidence in the reliability of the modeling predictions can only increase as a result of this exercise although no model can ever be fully validated. See Van der Heijde (1986) for a more detailed description of validation procedures.

7.5-3 Sensitivity Analysis

Once a model has been calibrated and validated, a sensitivity analysis should be performed on the model. This is accomplished by varying the values of input parameters where there is little field control and evaluating the resultant distribution in heads. If the model is very sensitive to reasonable changes in a parameter value (e.g.,

transmissivity, recharge, leakage), then caution should be exercised in interpreting results from the model, particularly under applied stresses differing from calibration conditions. Depending upon the importance of the forecasting capability of the model, (i.e., does the possible range of outcomes preclude adequate selection of alternatives or prediction of impacts), more field work may be required to decrease the uncertainty of the model in that area.

If the area where the uncertainty exists is in a remote part of the modeled area, determining more precise physical conditions may not be necessary. Leakage from or to a stream, however, may greatly alter head levels in an adjacent production well and hydrogeologic data will need to be more accurately quantified in that area. A sound conceptual model will aid in identifying sensitive areas early on in the program.

7.5-4 Forecasting

Upon completion of the calibration and verification procedures and at the conclusion of performing the sensitivity analysis, the model can be used to simulate past, current, and/or future conditions. One advantage of a numerical model is that, once calibrated, it can be used to simulate a variety of situations. A flow model can be used to predict the response of an aquifer to conditions of average or excessive recharge or to a drought. If a model is being used for long-term planning and prediction, it should be periodically recalibrated as new data becomes available. Caution should be exercised in attempting to use the model under conditions much different than those under which it was formulated and calibrated/validated.

7.6 REPORTING MODEL RESULTS

7.6-1 Presentation of Results

An important but often overlooked aspect in the use of groundwater models is the proper presentation of modeling results. In order to present modeling results in a systematic, clear and effective fashion, the following format is suggested. This format is an adaptation of the DEP Division of Water Supply's published Policy 87-12, "Quality Assurance for Groundwater Modeling".

7.6-2 Purpose

State the purpose, goals, and objectives of the modeling effort.

7.6-3 Conceptual Model

Develop and present a conceptual model of the aquifer system and, if applicable, the contamination problem of concern (i.e., existing distribution of contaminants and source characteristics). This should include cross-sections and maps of the geology and hydrology of the aquifer at an appropriate scale, including maps of the areal extent of the aquifer and if applicable, distribution of contamination, saturated thickness, water table and boundary conditions maps. Present pertinent available data with a discussion of its deficiencies.

7.6-4 Data Collection

Explain how, when, and by whom the data were collected, analyzed, and interpreted. Exploration methods and data-analysis techniques should be presented. The level of confidence in resulting parameter identification should be described. Describe how model results may be limited or restricted by the lack of knowledge about key aspects of the hydrogeologic system.

7.6-5 Model Description

Document the groundwater flow and contaminant transport model (software) that is being utilized. Include such information as the model name, its author(s) and the purpose for which the software was developed. The use of well documented and tested software is recommended over the use of custom or altered software. If an altered code is utilized, it should be thoroughly tested against a variety of known analytical solutions. The documentation must include the governing equation(s) being solved.

Explain why the model being utilized was chosen. All simplifying assumptions inherent to the application of the model should be stated and justified, as well as the impact these assumptions may have on model results. A comparison between these assumptions and actual conditions should be made. Describe where model assumptions and actual field conditions do not coincide and how this may affect model results.

7.6-6 Assignment of Model Parameters

All initial conditions, boundary conditions, hydraulic and transport parameter values should be defined and the reasons for selecting these conditions justified. The values assigned throughout the modeled area should be presented. The area covered by the model should be presented as an overlay on a topographic base map of appropriate scale, highlighting boundary conditions and hydraulic parameter values.

7.6-7 Model Calibration

Model calibration goals and procedures should be presented and discussed. The results of the final calibration run should be presented and analyzed and departure from the calibration targets analyzed. The effects of these departures on the model results should also be discussed.

7.6-8 Model Validation

If model validation has been performed, its goals and procedures should be presented and discussed. The results of the validation run should be presented and analyzed. Important points include departure from the validation targets and the significance of these departures. Present and discuss the overall model water and chemical balance, highlighting salient features of the model scenario (e.g., pumpage, recharge, leakage, or boundary conditions). Ideally, the validation should consist of a single run (per validation data set). If the validation run is not successful, but information is obtained of a suitable nature, it may lead to re-evaluation of the conceptual model and possible changes and further calibration.

7.6-9 Sensitivity Analysis

Model sensitivity analysis should be presented and interpreted. Determine what parameters of the model have the greatest influence on the model results. The analysis should focus on those parameters which utilize the least certain assumptions. Also indicate, on the basis of the sensitivity analysis, what the emphasis of future data collection efforts should be best to improve the model.

7.6-10 Data Preprocessing and Postprocessing

All preprocessing of model input data must be thoroughly described. Special precautions to avoid data input error must be applied and described. All postprocessing of model output data must be thoroughly described and any computer codes utilized must be documented. Note vertical exaggeration in any computer-generated cross-sections.

7.6-11 Model Prediction

The model output from all predictive scenarios should be presented and interpreted. Present and discuss the overall model water balance for each specific forecasting scenario. Show results in terms of new head distributions, rates of groundwater discharge, distribution of concentrations, and so forth. Discuss how model sensitivity and uncertainty could effect the predicted results.

7.6.12 Model Results

The physical reality of the model should be discussed (i.e., how well does the model represent the physical and chemical processes of the environment being simulated?). Restate the fundamental assumptions in the presentation of the model predictions. Note if the model results support the initial assumptions described in Section 7-7.4.

The model results should be presented both in technical and non-technical (i.e., layman's) terms. Model results should also be qualified, for example: "Given conservative values, within the range of expected variation, the model results show..." or "Given less conservative values within the range of expected variation, the model results show...".

7.6-13 Model Records

The modeler should provide/keep the following records on file in digital form:

- The version of the source code utilized;
- Input parameters, boundary and initial conditions;
- The final calibration run (input and output files); and
- All predictive runs (input and output files).

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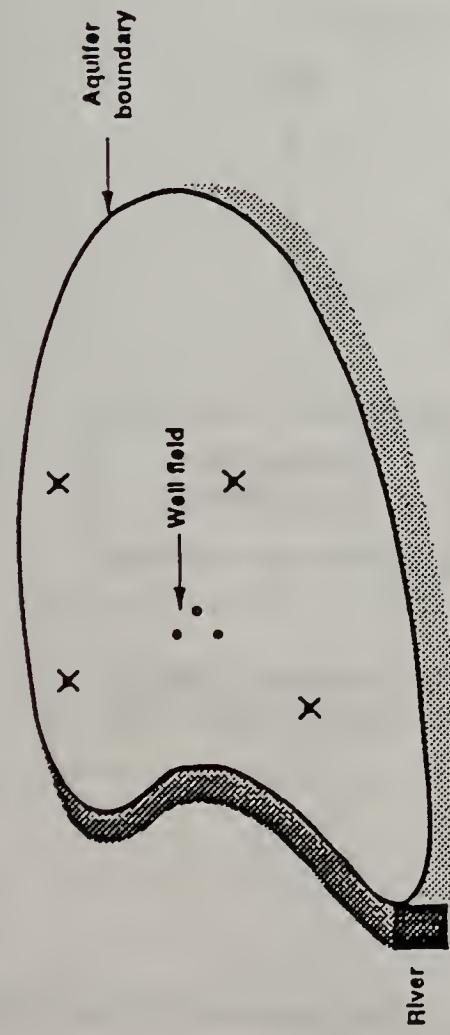
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LIST OF FIGURES

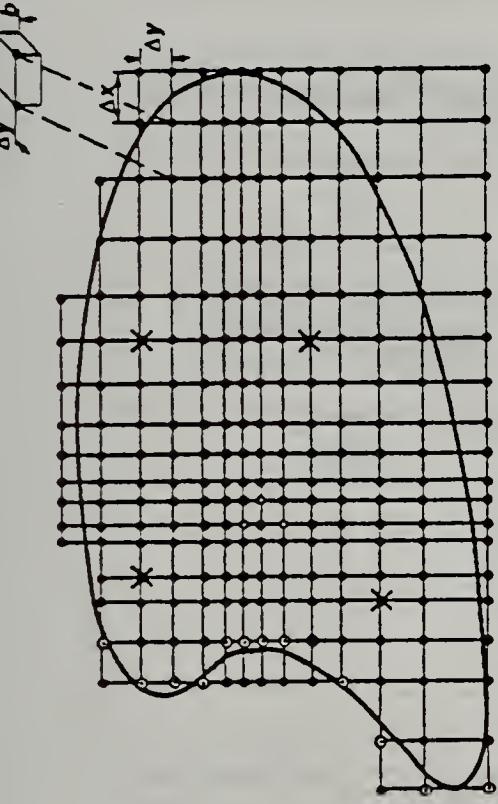
<u>Figure</u>	<u>Title</u>	<u>Page No.</u>
7-1	Finite Difference and Finite Element Representations of an Aquifer Region	35
	a. Map View of Aquifer Showing Well Field, Observation Wells, and Boundaries	
	b. Finite difference Grid with Block-Centered Nodes, Where Δx is the Spacing in the x direction, Δy is the Spacing in the y Direction, and b is the Aquifer Thickness	
	c. Finite difference Grid with Mesh-Centered Nodes	
	d. Finite element Mesh with Triangular Elements, Where b is the Aquifer Thickness .	
7-2	Flow Chart to Determine if Modeling is Required	36

LIST OF TABLES

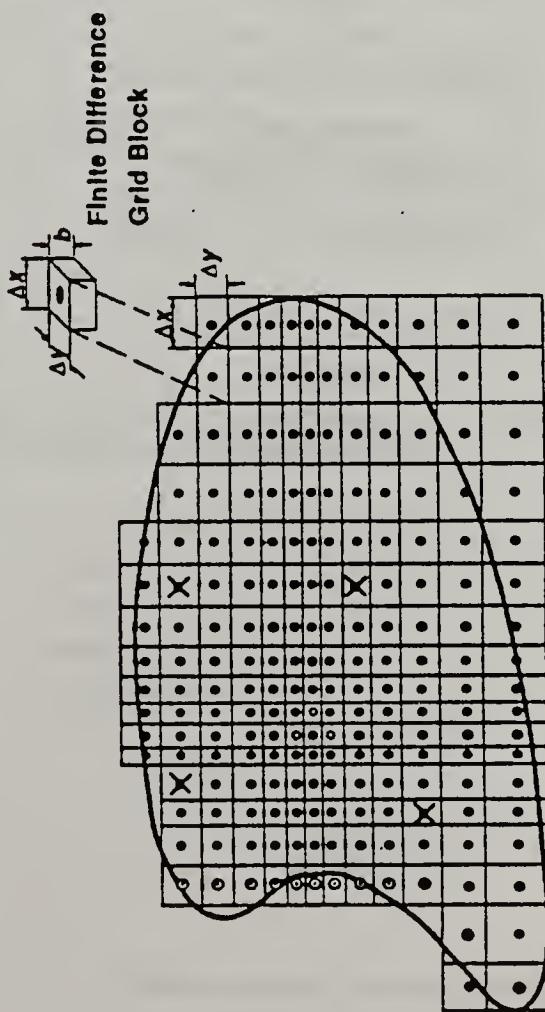
<u>Table</u>	<u>Title</u>	<u>Page No.</u>
7-1	Natural Processes that Affect Subsurface Contaminant Transport	37



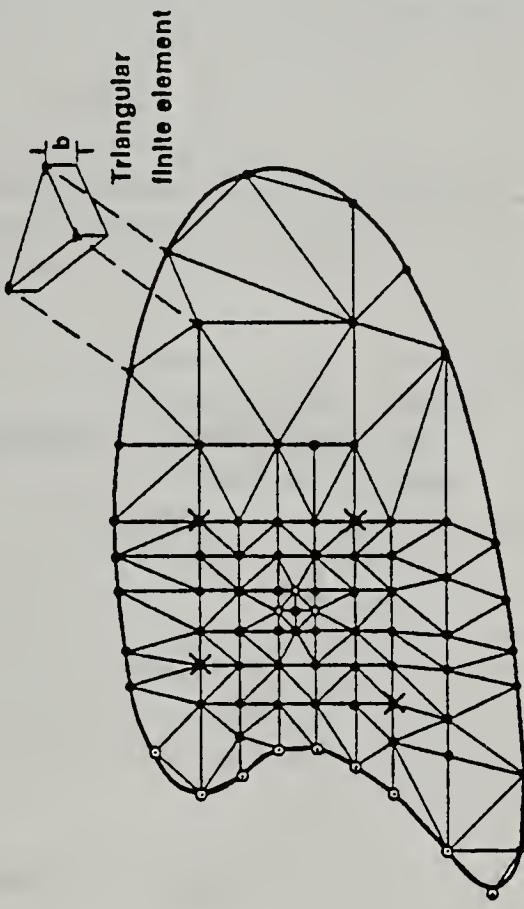
(a) Map View of Aquifer Showing Well Field, Observation Wells, and Boundaries.



(c) Finite Difference Grid With Mesh-Centred Nodes.



(b) Finite Difference Grid with Block-Centred Nodes, Where Δx is the Spacing in the x Direction, Δy is the Spacing in the y Direction, and b is the Aquifer Thickness.



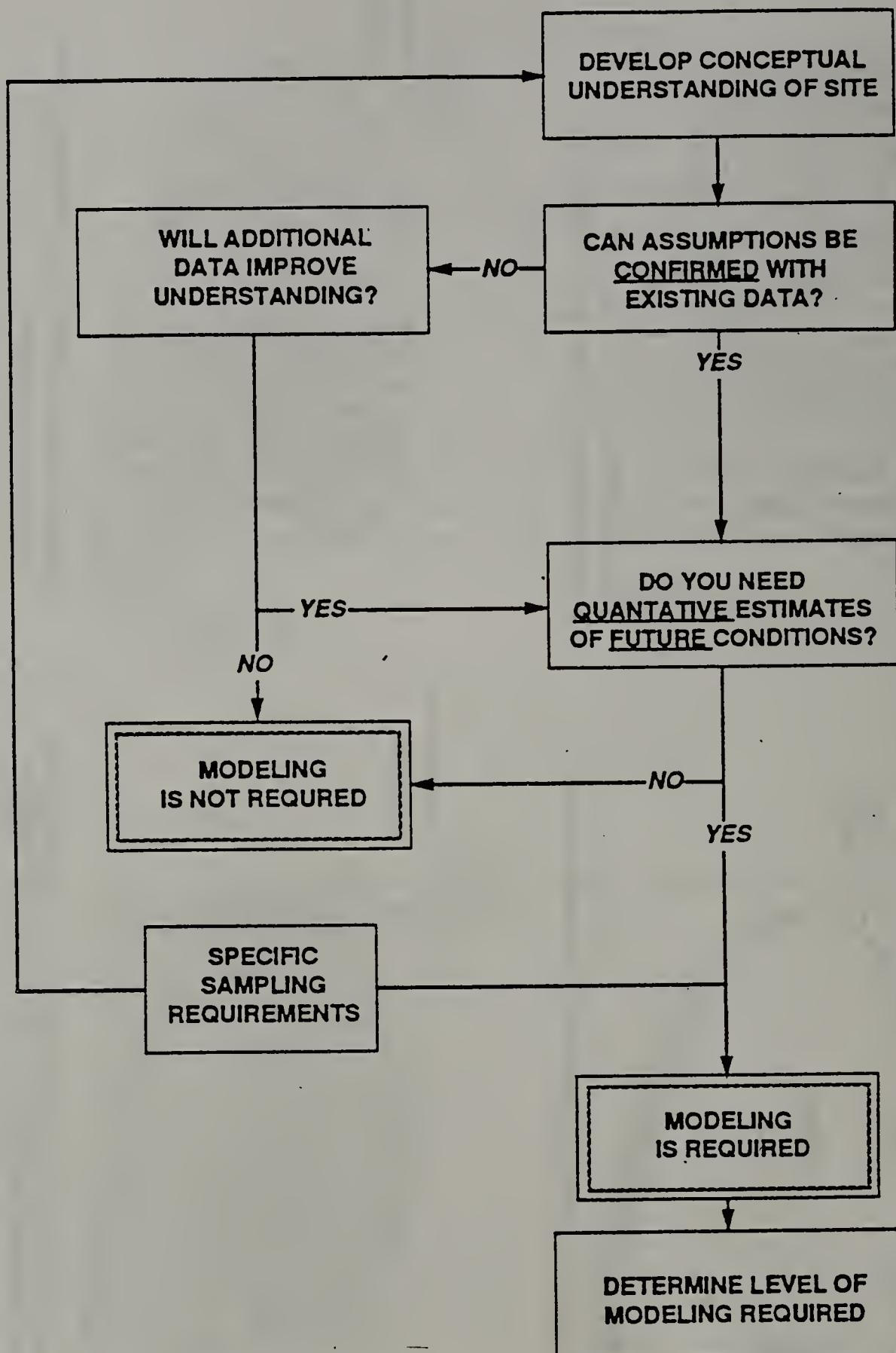
(d) Finite Element Mesh With Triangular Elements, Where b is the Aquifer Thickness.

Legend

- Node Point
- Source / sink node
- River node
- Observation Well
- X Observation Well (i.e. Pumping or Recharge Well)

Figure 7-1
Finite Difference and Finite Element Representations of an Aquifer Region

Source: Adapted from Wang and Anderson (1982)



Adapted from: Mercer and Faust (1981)

Figure 7-2
Flow Chart to Determine if Modeling is Required

TABLE 7-1

Natural Processes That Affect
Subsurface Contaminant Transport
(after Keely, 1987)

PHYSICAL PROCESSES

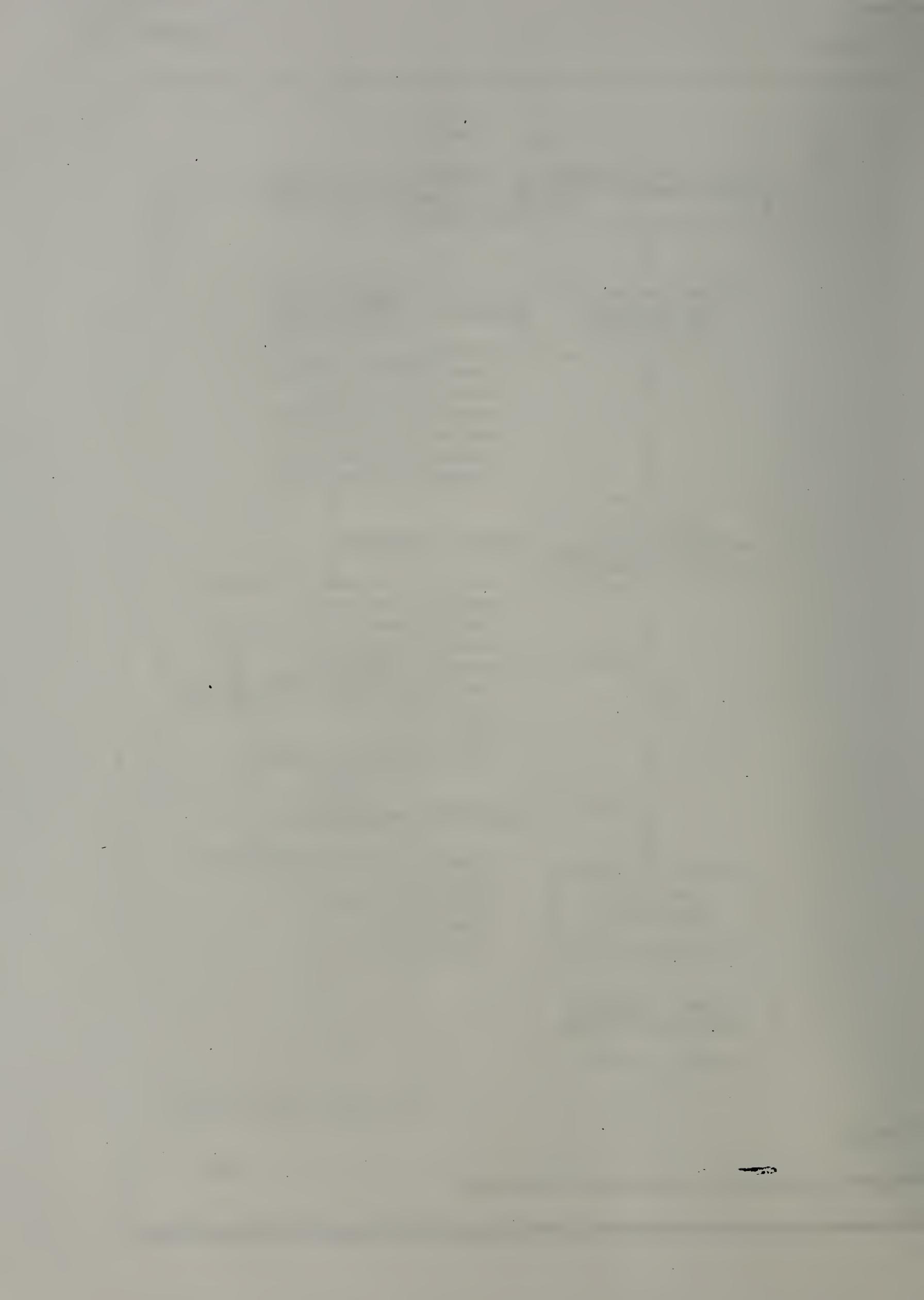
Advection
Hydrodynamic Dispersion
Molecular Diffusion
Density Stratification
Immiscible Phase Flow
Fractured Media Flow
Thermally Driven Flow

CHEMICAL PROCESSES

Oxidation-Reduction Reactions
Radionuclide Decay
Ion-Exchange
Complexation
Co-Solvation
Immiscible Phase Partitioning
Sorption
Hydrolysis
Precipitation/Dissolution

BIOLOGICAL PROCESSES

Microbial Population Dynamics
Substrate Utilization
Biotransformation
Adaptation
Co-metabolism



COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 8.1 INTRODUCTION

Section 8.1
Page i
November 1993

SECTION 8.1
INTRODUCTION

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.1	INTRODUCTION	1
8.1-1	Document Structure	2
8.1-2	Background Reference Materials	3

8.1 INTRODUCTION

A geophysical survey is an indirect method of determining the state of the subsurface in the survey area. By indirect, it is meant that the geophysical survey measures some physical property of the subsurface and uses the results to infer the material that caused it. Like a blind person trying to identify an object without the benefit of sight, the geophysicist cannot directly observe the subsurface but must instead rely on other, less direct methods of data collection to make his/her determination as to its state. Variations in the electrical field (applied and ambient), gravity and magnetic potentials, and seismic wave velocities, amplitudes and frequencies are systematically measured to infer the structure and composition of the subsurface soil, rocks and groundwater. Many geophysical methods produce results which by themselves cannot provide a definitive characterization of subsurface conditions; however, by using a combination of geophysical techniques (each of which measures a different physical property of the earth), the geophysicist can often eliminate incorrect possibilities to arrive at a correct interpretation.

The usefulness of geophysical techniques for site characterization and the evaluation of contaminated sites has been well-established during the past two decades. Determination of depths to both bedrock and the water table are routinely performed. Geophysical techniques are also used with great success to locate buried metal objects (barrels, tanks, pipes, trucks), certain migrating contaminant plumes, debris-filled trenches, determine the integrity of "cut off" slurry trenches, and trace the migration of contaminants through fractured bedrock.

Geophysical investigations in environmental studies are best used to:

- Characterize geologic conditions
- Determine the source and extent of contamination problems
- Optimize test pit and boring locations

In many cases, the proper application of a geophysical investigation adds significant information and reduces the costs necessary to acquire the information required to determine effective site remediation and cleanup. The correlation of geophysical data methods, with borehole geologic and sampling data will usually provide the most meaningful results.

The physical characteristics of a site which geophysics can help determine include: characterization of the types of overburden materials and thickness, as well as soil classification and permeability;

characterization of the types of bedrock and depth to bedrock; characterization of water table elevations, hydraulic gradients, groundwater flow direction; and identification and characterization of all other physical site characteristics such as buried utility lines, sewers, and water mains.

In certain instances, geophysics can also be used to help identify the source and extent of release of contaminants by helping to establish: the source(s) of releases of oil or hazardous material; the horizontal and vertical extent and (relative) concentrations of certain oil or hazardous materials in some media; the estimated volume of contaminated soil and (ground) water; some of the existing and potential soil and groundwater pathways; and the existence of certain plume(s) of oil or hazardous materials (ie, containing dissolved ionic contaminants) in the groundwater and the potential migration of the plume.

It should be noted that results of geophysical site investigations alone, rarely provide complete answers to the data requirements of an environmental investigation. An intrusive (e.g., soil boring) program is usually necessary to supplement a geophysical program. Results of the geophysical program, however, can minimize the number of borings necessary by optimizing their placement. In return, the borings provide important data which can be used to refine geophysical interpretations and results. Geophysical methods can provide accurate and inexpensive (in comparison with conventional intrusive techniques) measurements of average subsurface conditions over large areas, while borings provide detailed information for a limited area. A combined geophysical survey/boring program is therefore often the most cost-effective system for the complete analysis of site conditions.

8.1-1 Document Structure

This document has been divided into 3 sections and are as follows:

- o 8.1 Introduction
- o 8.2 Synopsis of Geophysical Investigation Methods
- o 8.3 Borehole Geophysical Methods

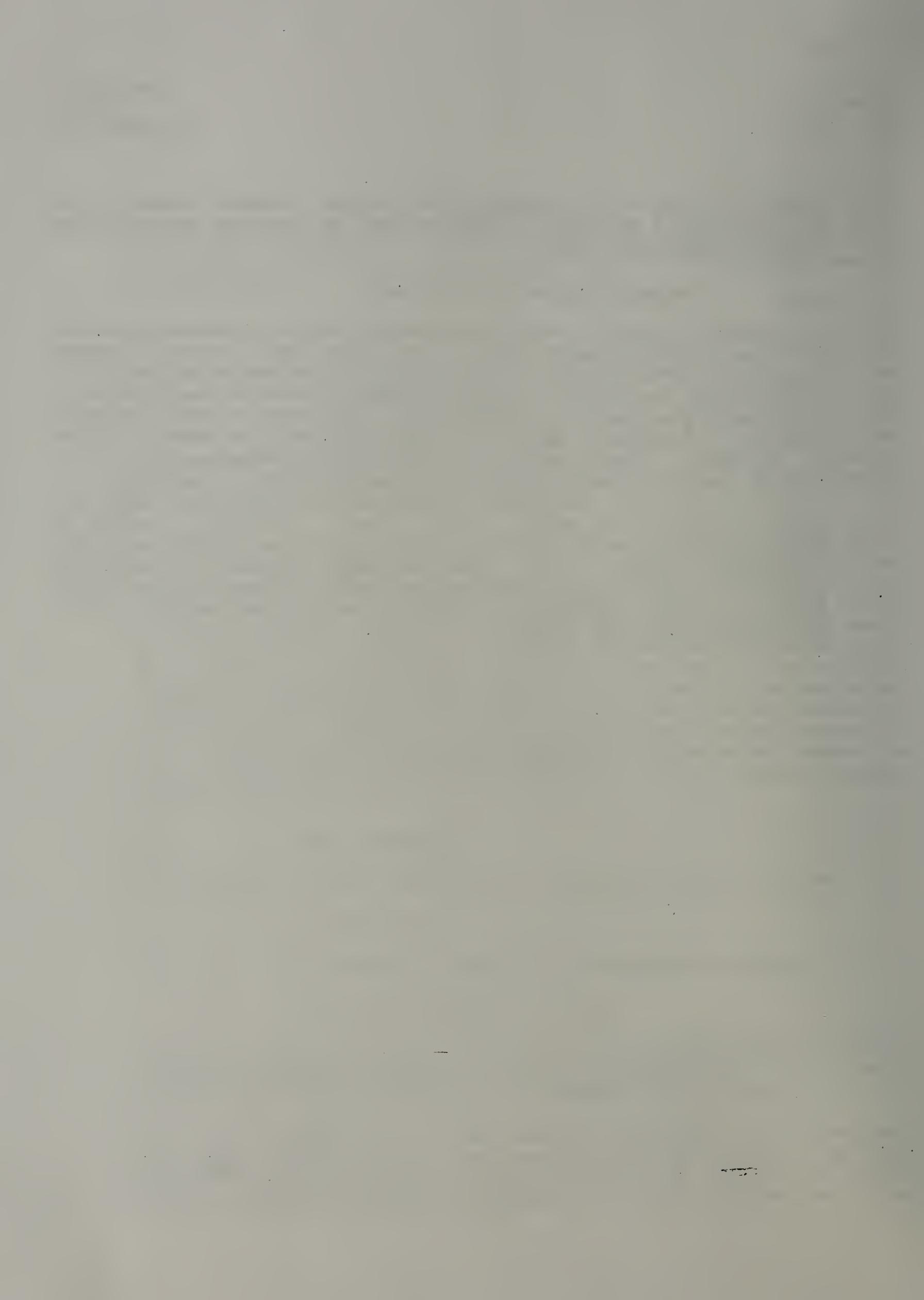
Section 8.2 is a synopsis of the geophysical techniques (excluding marine geophysical methods), which are covered in greater detail in the MADEP publication: Standard References for Geophysical Investigations.

The entire Chapter 10 of the Standard References for Geophysical Investigations (WSC 94-311) has been included as Section 8.3 of this document. Chapter 10 was included in its entirety to increase the utility of this document as a reference document, since this chapter covers the

suite of geophysical techniques which are commonly used in the investigation of subsurface conditions using soil borings and monitoring wells as measurement media.

8.1-2 Background Reference Materials

The reader is referred to the 1994 MADEP Publication: Standard References for Geophysical Investigations, WSC 94-311, for a more complete explanation of the methods briefly described in the following section. A comprehensive discussion of geophysical methods and their application to groundwater problems is included in the 1985 Electric Power Research Institute's Groundwater Manual for the Electric Utility Industry, Volume 3, Groundwater Investigation and Mitigation Techniques, Section 3. Another useful document providing a broad non-technical overview is a compilation entitled "Geophysical Techniques for Sensing Buried Waste and Waste Migration," by Benson et al. (1987). Additional sources of information for specific methods are referenced in the discussions of each geophysical method. Texts that generally discuss the applicable geophysical techniques include Dobrin (1976), Telford et al. (1976), Mooney (1977), U.S. Army Corps of Engineers (1979), Grant and West (1965), and Griffiths and King (1981).



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DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 8.2 SYNOPSIS OF GEOPHYSICAL INVESTIGATION METHODS

SECTION 8.2
SYNOPSIS OF GEOPHYSICAL INVESTIGATION METHODS

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.2-1	SEISMIC METHODS	1
8.2-1.1	Operating Principle	1
8.2-1.2	Applications	1
8.2-1.3	Limitations	2
8.2-2	RESISTIVITY METHOD	2
8.2-2.1	Operating Principle	2
8.2-2.2	Applications	3
8.2-2.3	Limitations	4
8.2-3	SELF-POTENTIAL METHOD	4
8.2-3.1	Operating Principle	4
8.2-3.2	Applications	5
8.2-3.3	Limitations	5
8.2-4	ELECTROMAGNETIC INDUCTION METHOD	5
8.2-4.1	Overview	5
8.2-4.1.1	Terrain Conductivity - Operating Principle	5
8.2-4.1.2	Terrain Conductivity Applications	6
8.2-4.1.3	Terrain Conductivity Limitations	7
8.2-4.1.4	VLF - Operating Principle	7
8.2-4.1.5	VLF - Applications	8
8.2-4.1.6	VLF - Disadvantages	8
8.2-5	GROUND PENETRATING RADAR (GPR)	9
8.2-5.1	Operating Principle	9
8.2-5.2	Applications	9
8.2-5.3	GPR Limitations	9
8.2-6	MAGNETIC METHODS	10
8.2-6.1	Overview	10
8.2-6.2	Applications	11
8.2-6.3	Limitations	11

SECTION 8.2
SYNOPSIS OF GEOPHYSICAL INVESTIGATION METHODS

TABLE OF CONTENTS
(continued)

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.2-7	GRAVITY METHOD	11
8.2-7.1	Overview	11
8.2-7.2	Applications	12
8.2-7.3	Limitations	12

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page No.</u>
8.2-1	Comparison of Geophysical Methods for Hazardous Waste Applications	14

8.2 SYNOPSIS OF GEOPHYSICAL INVESTIGATION METHODS

The following are synopses of the geophysical methods described in the MADEP publication entitled: Standard References for Geophysical Investigations, WSC 94-311. This section and the accompanying Table 8.2-1 offers a brief overview of the various methods. The reader is encouraged to consult the aforementioned publication for a more detailed discussion of the methodologies.

8.2-1 SEISMIC METHODS

8.2-1.1 Operating Principle

The seismic methods of geophysical exploration are active (manmade energy sources are used) techniques used to characterize subsurface geology. These methods are an indirect means of determining the type and thicknesses of the various materials underlying a site. The general principle of seismic surveying is that dissimilar subsurface materials can be determined by the differences in their respective physical properties. Each material has a unique set of physical properties, which affect the amplitude and velocity of seismic waves traveling through them. Seismic surveys are conducted by inducing seismic energy into the subsurface and measuring the resultant velocity and amplitude of the seismic waves by detectors located on the ground surface. The resultant data can be used to infer the types of material present in the subsurface.

There are two basic methods of seismic surveying: reflection and refraction. The basic methodology for these seismic techniques consists of actively generating waves in the ground and detecting them at ground surface after they have either reflected or refracted off of subsurface layers. The energy (seismic waves) is generated by various means such as weight drops, explosives, mechanical sources, sledge hammers, etc. Electromechanical transducers (which turn ground motion into electricity), called geophones, are used to detect the arrival time and amplitude of the induced ground motion. Arrays of geophones, called seismic spreads, are connected by electrically conductive cables to the seismograph, which processes and records the collected data. Recordings are made with either analog or digital seismographs. Preliminary data evaluation can usually be performed in the field with analog recordings. Playbacks of digital recordings are performed in the office for final data processing and report preparations.

Seismic refraction is by far the most prevalent method used in the shallow subsurface studies (less than 300 feet) employed during environmental investigations in Massachusetts and New England.

8.2-1.2 Applications

Seismic refraction surveys can be employed to: delineate the types and thicknesses of geologic materials; determine depth to groundwater;

correlate stratigraphy across a study area (in conjunction with test pit and/or boring log data); detect sinkholes and cavities; detect bedrock fracture zones; determine extent of landfills; and determine extent of filled areas such as reclaimed quarries.

When a seismic refraction survey is performed prior to an intrusive field investigation, the data can be used to help determine the number, distribution, and depth of test pits, borings, and monitoring wells.

When a seismic refraction survey is performed after intrusive field investigation, the use of physical data to calibrate refraction data allows the interpolation of subsurface conditions across large areas with a great degree of confidence. Intrusive field data can also be used to refine the interpretations of seismic data which had been collected prior to the start of the intrusive field program.

For larger investigations, especially those that require the delineation of bedrock competence and topography (DNAPL investigations), the combined use of seismic refraction with conventional investigative techniques can often result in a higher level of data volume and quality, while providing a considerable savings of time and money for the project.

8.2-1.3 Limitations

Seismic refraction does have limitations. The first is cost. Seismic refraction surveys cost between \$2,000 and \$4,000 per day. For smaller investigations, which might only require the installation of a few soil borings and water table monitoring wells, it probably would not prove cost effective to employ seismic refraction. Seismic refraction surveys by nature are sensitive to ground vibrations. Unfortunately, many human activities, including vehicle traffic, construction, and manufacturing, can create noise (unwanted ground vibrations) which can make collection of wanted data in a particular area difficult if not impossible. Seismic refraction surveying is seasonal. Frozen ground conditions make data collection difficult if not impossible. Interpretation of seismic refraction data is often non-unique. Some measured velocity values readily correlate with specific geologic materials such as massive, intact bedrock. Other velocity values, however, do not correspond to a unique interpretation of the nature of the materials surveyed and require correlation with soil borings or test pits for exact determination of the conditions and types of geologic layering.

8.2-2 RESISTIVITY METHOD

8.2-2.1 Operating Principle

Electrical resistivity surveying is an active geophysical technique that involves applying an electrical current to the earth and measuring the subsequent electrical response at the ground surface in order to determine physical properties of subsurface materials. The general principle of

resistivity testing is that dissimilar subsurface materials can be identified by the differences in their respective electrical potentials. Differences in electrical potentials of materials are determined by the application of a known amount of electric current to these materials and the measurement of the induced voltage potentials. Ohm's law states that the voltage (V) of an electric circuit is equal to the electric current (I) times the resistivity (R) of the medium ($V=IR$). Resistivity surveys are conducted by: 1) applying a known amount of electric current (I) to the earth; 2) measuring the induced voltage (V); and, using these two measurements, 3) determining the resistivity (R) of the volume of earth being surveyed.

Resistivity methods usually require that both current inducing and measurement electrodes to be pushed or driven into the ground. With connecting wires from the instruments to the electrodes, electrical current is introduced into the ground using the current electrodes and resistivity measurements are performed using different measurement electrode configurations and spacings. There are a number of standardized testing procedures, some of which are described in detail in this section.

Resistivity surveys identify geoelectric layers rather than geologic ones. A geoelectric layer is a layer which exhibits a similar electric resistivity response. A geoelectric layer can, but does not always, correspond to a geologic one. For example, an isotropic homogeneous sand, which is saturated with a fluid exhibiting a single conductivity response, will appear to be a single geoelectric layer. The same sand, if filled with fluid layers containing different conductivities, (i.e., salinities) will appear to be more than one geoelectric layer. The interpretation of resistivity data is therefore best made in conjunction with other geophysical techniques (i.e., seismic refraction) or conventional subsurface investigations (i.e., soil borings).

8.2-2.2 Applications

Historically, resistivity surveys have been used for a number of geologic mapping objectives including groundwater detection, sand and gravel mapping, bedrock depth determination, and other classic geologic exploration exercises. At present, these methods are commonly used to evaluate subsurface conditions as they relate to hazardous waste issues.

Resistivity measurements are commonly used to delineate either changes in resistivity with depth or lateral variations in resistivity. These applications are known respectively as:

- Vertical electrical soundings (VES)
- Horizontal profiling

VES surveys, which determine vertical resistivity changes, employ variable electrode spacings. VES surveys are used to identify geoelectrical

layering in soil and rock. These data are often used to identify: the groundwater table; clay layers; the bedrock surface; and to select optimum electrode spacings for horizontal profiling surveys.

For horizontal profiling, which determines lateral resistivity changes at a fixed depth of investigation, the current measurement electrode spacings are kept constant. Horizontal profiling is used to identify lateral resistivity variations in a survey area. Horizontal profiling can be used to detect conductive groundwater plumes (ie landfill leachate), landfill limits, geologic contacts, and sink holes (often present in limestone lithology).

Electromagnetic induction (EM) survey methods have generally supplanted resistivity surveys as the method of choice for shallow horizontal resistivity profiling because of EM's ease of use and increased data collection speed. Resistivity methods, however, provide better vertical resolution and are therefore superior to most EM methods for vertical resistivity profiling and for deeper horizontal resistivity profiling. Resistivity may also be applicable at sites where interferences from surface metal objects (e.g., fences) and/or power lines make the use of EM surveys impractical.

8.2-2.3 Limitations

Resistivity surveying methods can be carried out only in media which are neither extraordinarily conductive or resistive. Cultural interference (from powerlines, pipelines, and metal fences) is another serious limitation of resistivity surveying. Thin layers, or targets of limited lateral extent, may be undetectable because the measured potentials integrate the effects of a large volume of material. Because this technique measures geoelectric layers rather than geologic ones, the solution is nonunique. Therefore, in the absence of correlating data (e.g., boring logs) incorrect stratigraphic conclusions can be drawn. Differentiation between highly conductive materials (i.e., clay or salt water versus contamination plumes) may not be possible. A resistivity horizontal profiling survey is more labor intensive and time consuming than an EM survey.

8.2-3 SELF-POTENTIAL METHOD

8.2-3.1 Operating Principle

The self-potential (SP) survey method is a passive geophysical technique, which measures extremely small, naturally occurring voltage variations in the earth. The technique is based on the observation that when certain materials are in contact with either a different material (e.g., buried iron next to buried copper) or a localized change in the condition of the same material (e.g., interface of saturated and unsaturated condition), an electrical current is created. This current is readily detectable with inexpensive, portable voltage measuring instrumentation.

The technique is simple to operate, consisting of a series of measurements of electric potential (voltage) across two electrodes which are in contact with the ground and spaced at varying distances.

8.2-3.2 Applications

The most relevant application of this method to environmental investigations is the tracing of shallow leachate seepage zones when such zones are known to exist.

8.2-3.3 Limitations

Given the small size of the naturally occurring voltage differentials (measured in thousandths of volts), the SP method is extremely sensitive to man-made electrical interferences.

Although the technique is receiving increased attention for groundwater contamination assessment, the reliability and applicability of this methodology are inconclusive at this time.

8.2-4 ELECTROMAGNETIC INDUCTION METHOD

8.2-4.1 Overview

Electromagnetic Induction (EM) methods are non-destructive geophysical techniques for measuring the apparent conductivity of subsurface materials. As with resistivity surveys, the general principal of EM surveys is that dissimilar subsurface materials can be identified by the differences in their respective electrical responses to the introduction of an electrical stimulus. There are two basic types of EM surveys, terrain conductivity and Very Long Frequency (VLF). Each survey method is explained below. Terrain conductivity, given its broader applicability and usage in environmental studies, is explained in greater detail.

8.2-4.1.1 Terrain Conductivity - Operating Principle

Terrain conductivity surveys employ the same operating principals as conventional resistivity surveys (Section 4), but differ from a resistivity survey in the manner with which an electrical stimulus is introduced to the earth. The terrain conductivity method of EM surveying is an active geophysical technique that involves "inducing" an electric current in the subsurface and measuring the subsequent electrical response at the ground surface to characterize the physical properties of subsurface materials. In contrast, resistivity surveys directly apply an electrical current to the ground using current electrodes and measure the resultant voltage potential using measurement electrodes. The resistivity method requires that electrodes are driven into the ground and connected with wires at each survey point. Terrain conductivity surveys employ a transmitting coil, which is not directly coupled to the earth, to remotely induce a voltage potential in the ground and a remote receiving coil to

measure a secondary current created by the effect of the induced voltage in a conductive medium.

The name "terrain conductivity" stems from the different manner (with respect to resistivity surveys) with which terrain conductivity measures the electrical properties of the materials investigated. The resistivity method directly applies a current (I) to the ground, measures the resultant voltage (V), and calculates the resistivity (R) of the material measured (given that $V=IR$). Terrain conductivity surveys use a known current (I), passed through a transmitting coil to create an electromagnetic field which induces a voltage (V) in the ground. If the ground material is conductive, then a secondary (induced) electromagnetic field will be created. The terrain conductivity receiving coil measures the currents (I) created by the primary (transmitted) electromagnetic field and the secondary (induced) electromagnetic field. The ratio of these two currents is proportional to the conductivity (which is the inverse of resistivity; R) of the material being surveyed. (A more complete explanation of the inductive measurement theory is presented below in the Introduction.)

Terrain conductivity surveys identify geoelectric layers rather than geologic ones. A geoelectric layer is a layer which exhibits a similar electric resistivity response. A geoelectric layer can, but does not always, correspond to a geologic one. For example, an isotropic homogeneous sand, which is saturated with a fluid exhibiting a single conductivity response, will appear to be a single geoelectric layer. The same sand, if filled with fluid layers containing different conductivities, (i.e. salinities) will appear to be more than one geoelectric layer. The interpretation of terrain conductivity data is therefore best made in conjunction with other geophysical techniques (i.e., seismic refraction) or conventional subsurface investigations (i.e., soil borings).

8.2-4.1.2 Terrain Conductivity Applications

Common applications for terrain conductivity surveys include: conductive contaminant plume mapping; locating buried metallic objects and identifying landfill boundaries.

EM measurements are commonly used to delineate either changes in conductivity with depth or lateral variations in resistivity. These applications are known respectively as:

- Vertical electrical soundings (VES)
- Horizontal profiling

VES surveys, which determine vertical conductivity changes, are best conducted with instruments which allow variable coil spacings (e.g., Geonics EM 34). A limited (by depth of investigation) VES survey can also be conducted using a fixed coil spacing instrument (e.g., Geonics EM-31)

by altering the orientation (turning on its side) of the measuring equipment. VES surveys are used to identify geoelectrical layering in soil and rock. These data are often used to identify the groundwater table, clay layers, and the bedrock surface.

For horizontal profiling, which determines lateral resistivity changes at a fixed depth of investigation, the current measurement coil spacings are kept constant. A fixed coil spacing instrument can be operated by one person and is well suited for horizontal profiling. Horizontal profiling is used to identify lateral resistivity variations in a survey area. Horizontal profiling can be used to detect conductive groundwater plumes, landfill limits, geologic contacts, and sink holes (often present in limestone lithology).

As with other geophysical techniques, the effectiveness of terrain conductivity interpretation is increased by correlation with other geophysical techniques. For example, the combination of terrain conductivity and magnetometry surveys (Section 8) is ideal for a combination of location of buried drums while the combined use of terrain conductivity and seismic surveys (Section 3) will effectively differentiate between conductive contaminant plumes and landfill boundaries.

The terrain conductivity survey method is non intrusive and can be conducted at a more rapid pace (and less expensively) than conventional resistivity surveys. The portable instrument requires only a one or two person field party. Measured conductivity values can be observed during data acquisition, and yield immediate preliminary information for an experienced operator. For this reason, terrain conductivity survey methods have generally supplemented resistivity surveys as the method of choice for shallow horizontal profiling of the subsurface.

8.2-4.1.3 Terrain Conductivity Limitations

Limitations of the terrain conductivity method include the following. The instrument is effective for only a limited dynamic range (1 to 1,000 millimho/meter) of soil and conductivities. Terrain conductivity is sensitive to the presence of other EM fields, such as those associated with power lines and/or the presence of highly conductive objects, such as metal fences. Terrain conductivity has less vertical resolution than conventional resistivity surveys. The limited strength of the terrain conductivity transmitter signal, due to battery and coil size constraints (a compromise to portability), limits the instrument penetration to shallower depths than conventional resistivity surveys. Even simple stratigraphic layering cannot be distinguished without complex application and interpretation.

8.2-4.1.4 VLF - Operating Principle

The VLF survey method is an EM prospecting technique based on the principle of radio wave transmission and reception. The VLF method does

not employ an operator induced electromagnetic field, but instead utilizes low frequency transmissions from a submarine communications network established and maintained by the U.S. Navy as a power source.

VLF signals are transmitted by vertical radio antennae several hundred feet high with signal outputs ranging from 300 to 1,000 kWatts. The effective range of these transmitters as a VLF survey power source is on the order of thousands of miles. (It should be noted that a site must be a minimum of 50 miles from a transmitter for this technique to be effective.) A worldwide network of VLF stations has been established in such varied locations as Bordeaux, France (15.1 kHz), Moscow, USSR (17.1 kHz), and Cutler, Maine (24.0 kHz).

The field emitted by VLF antennae is horizontal, and its magnetic lines comprise concentric rings that "ripple" out from the transmitter. When this magnetic field encounters an electrically conductive structure on the surface or underground, weak secondary currents are generated around the structure. These currents create a secondary magnetic field.

VLF can detect long conductors such as electric cables, pipelines, and certain bedrock fractures. In order for the VLF method to be effective in detecting underground geologic structures, the structure must have: 1) the direction of its long axis within 30 degrees relative to a line tangent to the concentric rings that "ripple" from the transmitter (to initiate induction); 2) minimum dimensions of approximately 50 meters in length, 10 meters in depth, and about one meter in thickness; 3) a dip angle not less than 30 degrees from horizontal; and 4) higher electrical conductivity than the surrounding material.

Unlike terrain conductivity, the depth of VLF penetration is not a function of coil spacing, but rather the resistivity of the materials surveyed. Depth of penetration of VLF signals is directly proportional to (varies by approximately four times the square root of) the material's resistivity. For example, VLF signals propagating through granite (a highly resistive material) can penetrate to depths greater than 300 meters. However, a material such as salt water may limit depth of penetration to one to five meters.

8.2-4.1.5 VLF - Applications

The VLF receiver measures the current density due to the primary (transmitted) and secondary (induced) magnetic fields. From these measurements, structures such as water-saturated fracture zones, metallic ore bodies, mineralized zones, and long conductors such as electric cables or pipelines may be detected. The ability to detect water-filled bedrock fracture zones makes this type of survey method useful for bedrock water supply development and for site investigations which involve bedrock contamination.

8.2-4.1.6 VLF - Disadvantages

The VLF survey operator has no control over power source - VLF

transmitters are sometimes turned off for maintenance. Even when the transmitters are operating, the orientation (both strike and dip) of the object surveyed to the power source (which the operator also has no control over) will affect the success of the survey.

VLF data interpretation is difficult - VLF data does not provide data which can be directly related to subsurface conductivity. Interpretation is more subjective and therefore relies heavily on operator experience.

VLF survey limitations are: susceptibility to surface anthropogenic interferences (e.g., fences, automobiles, power lines). The effective depth of VLF investigation is extremely reduced in areas that contain shallow material of high conductivity.

8.2-5 GROUND PENETRATING RADAR (GPR)

8.2-5.1 Operating Principle

Ground penetrating radar (GPR) is an active geophysical system which transmits high frequency (80-1,000 MHz) electromagnetic waves (radar energy) into the ground and records the energy reflected back to the surface. It is a reflection technique similar to the single-trace seismic reflection method commonly used in marine subbottom profiling. The two techniques differ in that the seismic method uses audio frequency sound waves, while the radar method uses electromagnetic waves.

GPR is a continuous profiling method that transmits radar energy into the ground and records the radar energy reflected back by subsurface objects or layers. GPR is useful when a rapid survey with detailed vertical and horizontal control is desired. A GPR survey produces a graphic cross-sectional view of earth stratigraphy and targets (i.e., drums, pipelines, utilities, boulders, etc.) below the ground surface. Under optimum conditions, this method can be effective to depths of 70 feet (using commercially available equipment), although depth penetration is more often limited to the range of ten feet or less below ground surface.

8.2-5.2 Applications

GPR has been used to locate: underground storage tanks; underground pipes; buried drums; buried foundations; voids in rock and concrete; buried archaeological artifacts, excavations, filled pits and lagoons, and numerous other site specific applications and lithologic contacts. GPR can also be used to determine: stratigraphy; depth to the water table; and depth to bedrock. GPR has also been successfully used to delineate the lateral extent of contaminant plumes.

8.2-5.3 GPR Limitations

The limitations of GPR include the following. GPR survey lines must be cleared to ground level (e.g., may require cutting of brush and/or removal of obstructions). The depth of GPR signal penetration is highly dependent

on the materials present beneath the survey area (signal penetration in a saturated clay layer may be only a few inches). GPR interpretations are subjective, often requiring data corroboration using other geophysical methods and/or verification with borings or test pits.

To maximize resolution and minimize scattering losses, survey lines must be as smooth as possible to prevent bouncing and jarring the radar antenna. Survey lines cleared of debris also allow the antenna to be pulled at an even, continuous pace, permitting the easy determination of horizontal scale.

The depth of GPR investigation at a site is limited by soil type and/or the presence of high "loss" materials. Penetration of up to 75 feet has been reported for water-saturated, clean sands in a Massachusetts glacial delta using a commercial antenna. Signal penetration in saturated clays, on the other hand, is on the order of magnitude of only a few inches. In New England, the presence of glacial tills, and lacustrine and marine clays limit the depth of penetration. Delineation of materials beneath a conductive layer may also not be possible.

8.2-6 MAGNETIC METHODS

8.2-6.1 Overview

Magnetic surveying is a passive geophysical technique which measures the strength of the total magnetic field at any given point on the earth. The purpose of the magnetic survey in environmental investigations is to detect magnetic anomalies (variations in the expected field) which can be attributed to the presence of buried iron or steel objects. Magnetic surveys can also be used to locate bedrock fracture zones due to the fact that the hematite in fracture zones weathers to limonite, causing a change in magnetic signature.

Magnetism can be "induced" into materials which have a high magnetic susceptibility. Magnetic susceptibility is defined as the ability of a material to acquire a magnetization in the presence of a magnetic field (in this case the Earth's). The magnetic field induced is dependent upon the geometry, orientation, and magnetic properties of body, and the direction and intensity of the Earth's field. In order to recognize a magnetic anomaly, it must be several times larger than the background noise level along that profile.

Iron and steel (ferrous) objects have a high susceptibility and are therefore compatible with detection by magnetic survey methods. Buried ferrous metal objects such as steel drums or tanks cause local variations or anomalies in the earth's magnetic field that can be detected by a magnetometer. The size (amplitude) of this perturbation caused by the object is related to a number of factors such as the size of, distance to, and intensity of magnetization of the buried object.

Other non-ferrous metals, such as brass, copper, and aluminum, have low magnetic susceptibility and, therefore, will not be detected by a magnetic survey.

An instrument called a magnetometer is used in the performance of magnetic surveys. The magnetometer is used to determine the direction, gradient, and intensity of the total magnetic field. Various forms of magnetometers are used in land, airborne and marine type operations. The land instruments are lightweight and portable, and measurements are readily accomplished by a one or two person field party.

8.2-6.2 Applications

Magnetic surveys, performed as part of environmental investigations, are nearly always used to detect induced magnetism in iron and steel objects such as buried drums, pipelines, and underground storage tanks (USTs). The results of magnetic surveying can be used to direct excavation activities of buried drums and USTs.

The results can also be used to direct the placement of both upgradient and downgradient monitoring wells (in conjunction with data regarding the known or inferred direction of groundwater flow) to facilitate the assessment of potential releases of contaminants from these objects on water quality.

Magnetic surveys utilizing portable field magnetometers are relatively easy to perform and are usually the easiest to interpret with regard to siting drilling locations. Magnetic surveys, however, are susceptible to interferences from manmade structures such as utilities, buildings, and fences.

8.2-6.3 Limitations

Limitations of the magnetic survey method include the following. A magnetometer is susceptible to the interferences associated with the presence of other magnetic fields, such as those associated with power lines. Also, since the strength of the induced magnetic field is a function of the susceptibility of the material surveyed, the presence of highly susceptible objects, such as metal fences, also creates unwanted interferences. An anomaly of interest must be several times larger than the background noise (e.g., metal fences, remnant magnetism) to be detected. Interpretation is non-unique given the inherent complexity of dipole behavior and the fact that a number of different types and configurations of sources can cause the same anomaly.

8.2-7 GRAVITY METHOD

8.2-7.1 Overview

The gravity survey method is a passive geophysical technique which measures extremely small variations in the earth's gravitational field

using a highly sensitive instrument. In gravity exploration the variation in density of the surveyed area is the only significant factor. Lateral variations in the distribution of mass in the earth's crust produce distortions or differences in the gravitational field. Tectonics, faulting, erosion, deposition, and other geologic movement involving rock often result in lateral density variations in the subsurface rocks. Measured gravitational differences are interpreted in terms of probable subsurface mass distributions, which are inferred from surface and near surface geologic conditions.

8.2-7.2 Applications

The "microgravity" survey method produces data which allows more detailed or higher resolution interpretation than ordinary gravimetric measurements taken on a regional scale.

Microgravity measurements can be used to detect the following conditions: joint and fracture zones; dissolutions; collapses; cavities; buried river channels; and fault scarps. The detailed resolution of the microgravity survey is more suited to the limited areal surveys associated with environmental investigations and may be useful to characterize sites prior to drilling test wells.

The advantages of a gravity survey are that field work can be carried out by one to three persons in any accessible area, including highly developed urban and industrialized sites, over pavements, fills, landfills, on lake ice, and inside buildings. Instrumentation is portable; the work can be silent and produce no visible disturbance to an environment other than stakes or other station markings. The method lends itself well to areal coverage; contour maps of bedrock or other features have obvious advantages over information at points or along profiles.

8.2-7.3 Limitations

The sensitivity of the "Microgravity" instrumentation creates logistical problems including: a greater need for more detailed elevation data; a "quiet" site with regard to background vibrations that might affect the microgravimeter; as well as some inherent stability problems for the instrument itself.

The other limitations of a gravity survey are that: applications are limited to mapping of density-dependent interfaces; accurate station locations and elevations are necessary; calibration with geological "knowns" such as outcrops, borings, or seismic profiles is necessary for quantitative work; and excessive topography, access problems, and certain bedrock complexities may seriously limit the accuracy of data interpretation.

SECTION 8.2
SYNOPSIS OF GEOPHYSICAL INVESTIGATION METHODS

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page No.</u>
8.2-1	Comparision of Geophysical Methods for Hazardous Waste Applications	14

COMPARISON OF GEOPHYSICAL METHODS FOR HAZARDOUS WASTE APPLICATION

Geophysical Method	General Applications	Advantages	Limitations	Relative Cost	Depth of Investigation
Seismic Refraction	Determine the depths to bedrock, water table, glacial till. Identify zones of fractured weathered bedrock. Accuracy $\pm 10\%$ of depth to interface.	Accurately identifies soil and rock layering as reflected by contrasts in seismic compressional wave velocity values.	Does not detect contaminants in ground water. Sensitive to vibration, construction activities and electrical noise. Frozen ground precludes use of geophones and shot points.	Moderate to high	Shallow (0-10m) and deep (10-100+ m)
Electrical Resistivity	Determine depth to water table, clays, bedrock, etc. Accuracy $\pm 25\%$ of total depth. Identify highly conductive or resistive contamination plumes.	Equipment is inexpensive, easy to operate. Rapid method for determining ground resistivity layering.	Interpretation is not unique. Sensitive to fences, power lines, pipes, and other metal objects. Dipping strata complicates interpretation.	Moderate	Shallow (0-10m) and deep (10-100+ m)
Self-Potential	Identify ground water flow and area of contamination.	Equipment is inexpensive and easy to operate.	Highly qualitative interpretation. Susceptible to interference due to lithological and vegetation changes.	Inexpensive	Shallow (0-20m)
Electromagnetic Induction	Plume detection and tracing. Depths to water table, bedrock, clays, etc. Accuracy approximately $\pm 25\%$.	Walk-over method of determining ground conductivity	Lacks the vertical resolution and depth penetration of resistivity.	Moderate	Shallow (0-5m) and deep (5-60m)
Ground Penetrating Radar	Buried metal detection and general identification (drum, tank, debris, etc.). Accuracy $\pm 20\%$. Filled trench identification.	Tow-along method, equipment is commercially available, easy to operate, high resolution.	Depth of penetration limited by conductivity of material. Sensitive to shallow lithologic changes. Highly qualitative interpretation.	Moderate	Shallow (0-10m)
Magnetica	Buried (ferrous) detection.	Walk-over method, equipment easy to operate, commercially available. Rapid method for metal (ferrous) detection.	Interpretations not unique. Geologic data necessary for power lines, pipes, and cultural metal ferrous objects.	Inexpensive	Shallow (0-10m) and deep (10-100+ m)
Gravity	Detection of fault scarps, buried river channels, cavities, and collapse or fill areas.	Field work conducted by one person, data can be acquired in highly developed urban areas, equipment is portable.	High	Deep (10-100+ m)	
Borehole	Determine stratigraphy, fracture zones, porosity, permeability..	Rapid, most equipment easy to operate. Very good vertical resolution.	Low to Not Applicable	Moderate	Radioactive tools need special licensing. Borehole construction may limit techniques.

*All methods can be operated in a non-intrusive manner.

Comparison of Geophysical Methods for Hazardous Waste Applications

Table 8.2-1

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 8.3 BOREHOLE GEOPHYSICAL METHODS

SECTION 8.3
BOREHOLE GEOPHYSICAL METHODS

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.3-1	OVERVIEW	1
8.3-2	INTRODUCTION	2
8.3-2.1	Equipment	3
8.3-2.2	Field Procedures	3
8.3-3	PASSIVE BOREHOLE METHODS (NON-PENETRATING)	5
8.3-3.1	Borehole Television Camera Surveys	5
8.3-3.1.1	Principles of Operation	5
8.3-3.1.2	Applications	5
8.3-3.1.3	Equipment	6
8.3-3.1.4	Field Procedures	6
8.3-3.1.5	Interpretation	6
8.3-3.1.6	Advantages and Disadvantages	6
8.3-3.2	Caliper Logging	7
8.3-3.2.1	Principles of Operation	7
8.3-3.2.2	Applications	7
8.3-3.2.3	Equipment	7
8.3-3.2.4	Field Procedures	7
8.3-3.2.5	Interpretation	8
8.3-3.2.6	Advantages and Disadvantages	8
8.3-3.3	Temperature Logging	8
8.3-3.3.1	Principles of Operation	8
8.3-3.3.2	Applications	8
8.3-3.3.3	Equipment	9
8.3-3.3.4	Field Procedures	9
8.3-3.3.5	Interpretation	9
8.3-3.3.6	Advantages and Limitations	9

SECTION 8.3
BOREHOLE GEOPHYSICAL METHODS

TABLE OF CONTENTS (continued)

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.3-3.4	Self Potential (SP)	10
8.3-3.4.1	Principles of Operation	10
8.3-3.4.2	Applications	10
8.3-3.4.3	Equipment	10
8.3-3.4.4	Field Procedures	11
8.3-3.4.5	Interpretation	11
8.3-3.4.6	Advantages and Disadvantages	11
8.3-3.5	Fluid Resistivity	11
8.3-3.5.1	Principles of Operation	11
8.3-3.5.2	Applications	12
8.3-3.5.3	Equipment	12
8.3-3.5.4	Field Procedures	12
8.3-3.5.5	Interpretation	12
8.3-3.5.6	Advantages and Limitations	13
8.3-3.6	Inhole Flow Measurement (Flowmeters)	13
8.3-3.6.1	Principles of Operation	13
8.3-3.6.2	Applications	14
8.3-3.6.3	Equipment	14
8.3-3.6.4	Field Procedures	15
8.3-3.6.5	Interpretation	15
8.3-3.6.6	Advantages and Limitations	16
8.3-4	FORMATION PENETRATING METHODS	17
8.3-4.1	Resistivity Techniques	17
8.3-4.1.1	Principles of Operation	17
8.3-4.1.2	Applications	18
8.3-4.1.3	Equipment	18
8.3-4.1.4	Field Procedures	18
8.3-4.1.5	Interpretation	19
8.3-4.1.6	Advantages and Disadvantages	19
8.3-4.2	Acoustic (Sonic) Methods	20
8.3-4.2.1	Principles of Operation	20
8.3-4.2.2	Applications	22
8.3-4.2.3	Equipment	23
8.3-4.2.4	Field Procedures	23
8.3-4.2.5	Interpretation	24
8.3-4.2.6	Advantages and Disadvantages	24

SECTION 8.3
BOREHOLE GEOPHYSICAL METHODS

TABLE OF CONTENTS (continued)

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.3-4.3	Nuclear (Radiation) Methods	25
8.3-4.3.1	Principles of Operation	25
8.3-4.3.1.1	Natural Gamma-ray Log	25
8.3-4.3.1.2	Gamma-gamma Log	25
8.3-4.3.1.3	Neutron-epithermal-neutron Log	26
8.3-4.3.2	Applications	26
8.3-4.3.3	Equipment	27
8.3-4.3.4	Field Procedures	27
8.3-4.3.5	Interpretation	27
8.3-4.3.6	Advantages and Disadvantages	29
8.3-4.4	Vertical Seismic Profiling (VSP)	29
8.3-4.4.1	Principles of Operation	29
8.3-4.4.2	Applications	30
8.3-4.4.3	Equipment	30
8.3-4.4.4	Field Procedures	31
8.3-4.4.5	Interpretation	31
8.3-4.4.6	Advantages and Disadvantages	32
8.3-5	GLOSSARY	32
REFERENCES	34

SECTION 8.3
BOREHOLE GEOPHYSICAL METHODS

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page No.</u>
8.3-1	Typical Geophysical Logging Setup	38
8.3-2	Caliper Probes	39
8.3-3	Interpretation of Borehole Temperature Profiles .	40
8.3-4	SP Log Example	41
8.3-5	Example of Flowmeter Log	42
8.3-6	Resistivity Probes	43
8.3-7	F versus ϕ Plot for Sandstones	44
8.3-8	Acoustic Velocity Logging	45
8.3-9	Acoustic Televiewer Diagram	46
8.3-10	Example of Acoustic Televiewer Image	47
8.3-11	Example of Cross-plot of Acoustic Velocity and Neutron Logs with Geologic Interpretation	48
8.3-12	API Gamma Ray Units for Various Tertiary Sediments	49
8.3-13	Tube Waves Generated by Seismic Energy Incident on Permeable Fracture Zones	50
8.3-14	VSP to Determine 3D Geometry of Strata, Moduli Values and Permeability	51
8.3-15	Relationship Between Hydraulic Conductivity and Ratios of Tube Wave to P Wave Amplitudes as a Function of Frequency	52

SECTION 8.3
BOREHOLE GEOPHYSICS

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page No.</u>
8.3-1	Common Borehole Logging Techniques	54
8.3-2	Compressional and Shear Velocities in Rocks . . .	55

8.3 BOREHOLE GEOPHYSICAL METHODS

8.3-1 OVERVIEW

Borehole geophysical surveys are designed to provide a continuous vertical profile of the soil, rock and water conditions immediately adjacent to the borehole. Logging is accomplished by lowering probes into the borehole to measure the electrical, acoustical, or radioactive properties of the materials surrounding a borehole. The surveys are non-destructive and can often be run in existing boreholes, monitoring wells, and water wells with no modifications.

Borehole geophysical methods are used primarily to characterize rocks, correlate overburden or rock units, and determine physical and hydrologic properties. Table 8.3-1 provides a listing of the applications for the methods described in this section. Specific applications include determining porosity, locating clay layers, determining water quality, estimating permeability, and finding fracture zones and zones of water loss or gain. More detailed discussion of the theory and interpretation of the use of borehole geophysical methods in groundwater investigations is presented by Keys and MacCary (1971), Kwader (1982), and Collier and Alger (1988).

The primary advantage of borehole methods is that they provide an unbiased, high density of measurements of soil, rock and water properties at precise depths. Borehole methods are fast and generally unaffected by surface features such as power lines, buildings and railroad tracks. Little data reduction is necessary before most logs can be interpreted; often preliminary interpretations can be made as they are being run. Borehole logging is non-destructive and can often be run with no modifications in existing cased or uncased boreholes and in the screened and unscreened intervals of monitoring wells.

Some borehole methods, such as the temperature log (a log is the printed display of the parameter being measured vs. the depth where the measurement is taken), the caliper log, and the flowmeter log are relatively simple to operate and the data recordings are easy to interpret.

Other methods, such as logging with an active nuclear source and resistivity logging are much more complex for operation and/or for data interpretation. Borehole geophysical logging using such methods is a technical speciality that requires complex electronic equipment to be operated according to exact design specifications. Since no two boreholes exhibit the same geophysical response, and as responses can not be quantitatively validated during logging, the quality of a log depends strongly on the operator's experience and judgment.

The radius of investigation for most probes is commonly less than one foot. Depending on the permeability of the formation and the drilling techniques applied, the condition of materials investigated may be altered by the drilling method. The borehole surveys may therefore provide only

limited representation of true formation properties.

Borehole geophysical methods may not be cost-effective for typical environmental investigations in Massachusetts, where shallow overburden wells dominate. Borehole geophysical methods are best suited for deep bedrock wells, where the information gathered will be most useful. When natural in-situ conditions are present, and several deep boreholes are logged and correlated, often very large areas can be geologically characterized with a minimum of time and cost.

8.3-2 INTRODUCTION

Borehole geophysical techniques (also called logging) are a group of active and passive geophysical methods used to provide detailed physical properties of soil, rock, and water. The term "active" implies subjecting the area around and in the borehole to a stress (either electric, thermal, acoustic, etc.) in which a response can be measured (formation-penetrating methods), while "passive" involves measuring only naturally-occurring conditions (non-penetrating methods).

Table 8.3-1 shows the array of available borehole techniques keyed to types of subsurface information desired and limitations posed by borehole conditions. Many of the techniques are based on counterpart surface geophysical methods, adapted to the borehole environment. Typically, these adaptations include the reduction of equipment size (the probes for most techniques will fit inside a 2-inch diameter hole), reduction and standardization of the fixed source to receiver spacing (and sometimes a corresponding reduction in the depth of investigation), protection of probes from pressure and temperature effects, and interpretation of data with respect to vertical rather than horizontal changes.

Borehole geophysical logging methods to be discussed are:

- Downhole television camera
- Caliper
- Temperature
- Electrical methods (Single-point-resistance, Normal resistivity, SP, Fluid resistivity, Electromagnetic/Induction)
- Flowmeter
- Acoustic methods (Velocity, Waveform, Acoustic televiewer)
- Nuclear methods (Natural gamma, Neutron, Gamma-gamma)
- Vertical seismic profiling

Use of more than one logging technique is generally necessary to determine soil and water properties adjacent to the borehole. Because each probe has a different response, these logs are interpreted by cross-comparisons

to determine specific characteristics of interest. For example, caliper, single-point resistance, acoustic and thermal logs may be run as a suite to identify fracture zones in rock.

8.3-2.1 Equipment

Figure 8.3-1 shows a typical geophysical logging set up. The surface and downhole equipment used in borehole geophysical surveys is connected by the logging cable. The cable provides transmission of electrical power to the downhole probe and a return path for signals generated in the probe. Cables are usually one- or four-conductor, insulated, wire-wrapped (shielded), and chemically stable.

Equipment on the ground surface at the hole includes:

- Power supply (AC or DC)
- Instrument and probe controls (on/off, open/close caliper, scale setting)
- Winch and depth counter
- Signal receiving and conditioning circuits
- Recorder and/or portable computer
- Well head cable tripod or sheave

Downhole equipment includes the measuring probe which is connected to the cable by a threaded water-tight coupling. Two or more logging methods can occasionally be performed with the same probe (e.g., SP and normal resistivity). Probes can be changed quickly so that a number of logs can be performed at one borehole with minimal down-time.

Some logging systems are equipped with digital data acquisition systems connected to portable personal computers. Data are sampled at regular intervals (usually six inches or one foot) and stored on magnetic tape or disk. This setup is highly desirable because digital data can be manipulated easily for calculations or presentation. Although tedious, analog data can be digitized at the office using available digitizing hardware and software.

8.3-2.2 Field Procedures

Field procedures for logging generally consist of six steps, as outlined below:

- Equipment setup and assembly
- Verification (or calibration) of probe functions at surface
- Downhole run and total depth determination

- o Main run (uphole as appropriate)
- o Repeat run (if verification of anomalies warrants)
- o After-run calibration

Calibration measures the probe's response to a known standard. Checking the probe response against a known standard before and after a borehole survey ensures that the probe is operating and measuring correctly. After the probe response is calibrated, it is placed at the top of the borehole and the reference point of the probe is positioned at a reference elevation (usually ground surface or top of casing). The depth counter is then set to either zero or ground zero and the probe is lowered to the bottom of the hole. This process is known as depth calibration.

It is customary practice to make a record of log response when lowering most probes to the bottom, although a formal depth-registered log is normally not necessary or practical. However, it is important that the downhole run document the extremes in order to choose the optimal instrument settings for the uphole run, during which a formal depth-registered log is made. (Uphole and downhole recorded logs will not be identical for most geophysical probes because of probe design and delayed response in the direction of probe movement.)

The temperature and fluid resistivity probes are run from top to bottom so that the water in the borehole is not mixed or displaced appreciably by moving the probe. All other geophysical surveys are recorded during probe ascent in the borehole so that constant logging speed and cable tension can be maintained.

Once the probe reaches the bottom of the hole, the optimal instrument settings are activated, and the uphole log is made. The footage dial reading on the winch is recorded on the field chart (analog recorder paper) at the exact point of pen stoppage at the top of the hole to verify depth calibration. Agreement between pen and dial should be within 0.5 foot.

Analog recordings are usually made at a vertical (depth) scale of one inch equals 10 feet; however, a different scale may be used to show more detail, or less detail, if a digital recording is made simultaneously. If the data are not digitally recorded, it is very important to select instrument settings that will result in nearly full chart-width pen fluctuation without reaching the margins of the chart paper. Generally, one set of instrument settings can be selected to achieve this result for the entire depth logged. All setting changes must be accurately documented on the chart (beside the change or in the header). If the log appears uncharacteristic or suspect, the probe calibration is checked. A second complete or partial log should be made if any doubts persist concerning instrument/probe response.

When contaminants are (or may be) present, the cable must be decontaminated as it is removed from the well. When multiple logs are to

be run in shallow wells, it is desirable and usually possible to set up the logger at a distance adequate to prevent the wet cable from wrapping on the spool between runs. In this case, cable decontamination is needed only after the last probe is extracted. A preliminary rinse should be performed while the cable is over the borehole. One method for decontamination is to set up stations along the cable for washing and rinsing (for a more thorough discussion of decontamination procedures, see Sections 3.3 and 6.5) as shown in Figure 8.3-1. Another method is to construct a jig to hold sponges and fluids for washing, or properly-attired field personnel can perform decontamination using spray bottles and sponges.

Downhole probes that will be in direct contact with potentially contaminated soil and water must be decontaminated between logging runs. Probes should also be thoroughly decontaminated, taking care to remove all contaminants from moving parts (e.g., hinges on caliper arms). Without decontamination, contaminants can be transferred onto the spool, contaminating the remainder of the cable or other boreholes.

Borehole methods that employ the use of radioactive sources should only be used in boreholes that are either cased or completed in competent bedrock. Operators of probes with radioactive sources must be certified and licensed by the United States Nuclear Regulatory Commission.

8.3-3 PASSIVE BOREHOLE METHODS (NON-PENETRATING)

8.3-3.1 Borehole Television Camera Surveys

Although the borehole television camera is not technically a geophysical logging method, it is discussed in this section because of its usefulness in the investigation of open hole bedrock wells and the evaluation of casing integrity.

8.3-3.1.1 Principles of Operation

A borehole television camera survey can be made of any well or boring of appropriate diameter that is filled with clear water or air. The camera, similar to a home video camera, is enclosed in a watertight, pressure-safe housing that contains a light source. A coaxial cable is attached to the camera and the light source. The cable allows the transmission of power to the downhole instruments and the transmission of video signal from the camera. Video signals sent up the coaxial cable are viewed on a television monitor at the surface. The survey is also recorded on videotape to permit future analysis.

8.3-3.1.2 Applications

Borehole camera surveys are generally used for inspection of cased borehole sections. Camera surveys can reveal mechanical defects in casing such as:

- o Cracks, holes and splits

- o Oxidation (rust) of steel casing
- o Scaling by contaminants
- o Plugging of slots or screen

In an open hole, the borehole camera can assist in determining rock type, layering, the presence of fracturing, and hole integrity.

8.3-3.1.3 Equipment

A number of borehole camera systems are commercially available. These systems are generally composed of a downhole camera with light source, hand or light duty electric winch with coaxial cable, television monitor, camera control panel, and video tape recorder. Manufacturers' specifications and options, which may vary considerably among systems include:

- o Probe size (1½-inch to 6-inch diameters are available)
- o Black-and-white or color recording capabilities
- o Size and quality of television monitor
- o Camera lens quality (amount of distortion)
- o Up-hole remote controls (amount of light, focus, and aperture setting)
- o Text and depth printed on log (recording)

Borehole cameras need a special coaxial cable for transmission of video data.

8.3-3.1.4 Field Procedures

Camera systems that do not have remote controls for adjustment of focus, amount of light or aperture must be lowered into the hole, checked for picture quality then removed and adjusted if necessary. The camera system should be raised and lowered slowly in the borehole to avoid stirring up sediment that may have settled in slots, the screen, or on the bottom.

8.3-3.1.5 Interpretation

The visual inspection of a borehole or casing requires no special interpretation techniques.

8.3-3.1.6 Advantages and Disadvantages

The borehole camera can provide a very accurate picture of the mechanical condition of the boring and casing. Small features such as open fractures and clogged slots and screens can be observed with this technique.

Resolution of the camera varies considerably between manufacturers. The camera's resolution may not be high enough to show hairline fracturing.

Water clarity is usually a limiting factor in the use of borehole camera surveys. The possible effect of contaminants on the optical lens of the waterproof case should be considered before running a survey. Also, the borehole camera cannot be attached to a standard one- or four-conductor logging cable like those used for electrical, nuclear or caliper logging.

8.3-3.2 Caliper Logging

8.3-3.2.1 Principles of Operation

The caliper tool measures the diameter of the borehole. Spring-loaded arms, hinged to the probe body at their upper end, press against the borehole wall. The hinged end of the arm is connected to a variable resistor. As the arm moves out (in an enlarged section of the borehole), the resistance is lowered and a larger voltage is sent to the recorder and displayed is a change in borehole diameter. Figure 8.3-2 illustrates a three-arm and a four-arm caliper.

8.3-3.2.2 Applications

The caliper log is generally used to assess the variation in hole diameter for use in conjunction with other geophysical logging techniques that are sensitive to borehole size and smoothness (e.g., gamma-gamma, neutron, acoustic velocity). When appropriate, caliper log data may be used to determine corrections to other logs. Caliper logs can also be used to find fractures, solution channels, and vugs in hard rock, or to identify depths at which soft formations may be squeezing into the hole and substantially restricting other downhole testing.

8.3-3.2.3 Equipment

The most common and accurate of the caliper probes has three or four arms. Probes with four arms provide two diameters (maximum and minimum). The surface electronics contain opening and closing controls for the probe arms, as well as controls for calibration setting. Both the three and four arm models are calibrated using two different size rings of known diameter.

8.3-3.2.4 Field Procedures

No information can be obtained on the downhole run because the arms will not function properly in this direction. The caliper arms are opened at the bottom and a log is made pulling the probe uphole at a relatively slow rate of 8 to 15 feet per minute. In partially cased holes, the probe should be run in the casing to verify diameter calibration and check for major casing breaks, if this information is desired.

8.3-3.2.5 Interpretation

The interpretation of the caliper log is straightforward because the hole diameter is recorded directly in inches. Three-arm calipers tend to show the maximum hole size, while four-arm calipers will also show minimum hole size. Fractures, if they are non-vertical, show as sudden increases in borehole size. Fractures less than about 1/4 inch in aperture or those that intersect the borehole at a steep angle may not affect the position of the probe's arms, and go unrecognized.

8.3-3.2.6 Advantages and Disadvantages

The caliper tool gives a good indication of the rugosity (degree of roughness) of the borehole. Data are relatively simple to interpret and should always be run if logging an uncased borehole. The probe requires inspection and possibly cleaning of arm hinges before using to prevent a loss of sensitivity to diameter changes.

8.3-3.3 Temperature Logging

8.3-3.3.1 Principles of Operation

Temperature logging provides a vertical profile of temperature (or differential temperature) in a water-filled borehole. The probe is quite simple and features a thermistor (temperature-dependent resistor) mounted at its bottom end. The voltage across the thermistor is sent to the uphole circuits, voltage readings are converted to counts per second (cps) and cps fluctuation versus depth are recorded directly on the log. Each probe and surface electronics system has a laboratory-derived relationship between cps and temperature in degrees Celsius.

A more sensitive version of the temperature log, called the differential temperature log, is a calculation of the change in temperature between two points in the borehole. Differential temperature probes may contain two thermistors a fixed distance apart, or may contain one thermistor and calculate temperature changes electronically by comparing the present reading to stored data from previous readings.

8.3-3.3.2 Applications

The temperature log is used to help identify the source and movement of water in the borehole. The specific applications include:

- o Location of zones of water flow
- o Location of leaks in casing
- o Identification of discrete aquifers
- o Indication of permeability

Temperature logging can also be used to identify the location of cement outside the casing in a grouted hole if the probe is run within 24 hours of cementing.

8.3-3.3.3 Equipment

The equipment needed to run a temperature log includes a thermistor mounted on the end of the probe and protected by a thin metal cage, and a voltage-controlled recorder. The equipment is relatively simple to operate. The typical temperature probe can resolve differences in temperature of 0.02°C , and high-resolution equipment can attain a precision of about 0.001°C .

8.3-3.3.4 Field Procedures

The temperature probe should be the first log run in a borehole if it is to be included in the investigative suite. It should be run from top to bottom to avoid mixing of the water. It is especially important to run the differential temperature probe at a very slow and consistent speed (6 to 8 ft/minute is recommended) so that physical mixing of thermally stratified water will not occur.

Generally, the temperature probe is not field-calibrated. However, its calibration can be crudely checked in air or water if another temperature measuring device is available. The responsiveness of the probe and recorder electronics can be verified by breathing on the thermistor.

8.3-3.3.5 Interpretation

Normally, interpretation of the temperature log is based on the assumption that water in the well is at thermal equilibrium with the surrounding material. Water entering a well bore from different aquifers penetrated by the hole usually will have a different temperature and will cause a flattening or steepening of the log profile. Figure 8.3-3 demonstrates the standard interpretation of various configurations of temperature profiles. An abrupt anomaly on the log is caused by either warmer or cooler water entering or leaving the borehole at the depth of the anomaly. Permeable zones, especially major fractures and casing leaks, can thus be detected as anomalous points on the temperature logs if any groundwater movement is occurring.

8.3-3.3.6 Advantages and Limitations

A temperature log must be made in a fluid-filled hole. The preferred situation for most investigations requires that a borehole has reached thermal equilibrium with the surrounding material and that this equilibrium has not been disturbed by sampling or other downhole activities. Depending on subsurface permeabilities and the degree of thermal disturbance, the equilibration time can vary from a day to perhaps several weeks. In order for this log to reflect natural subsurface conditions, it is also necessary that surficial water does not enter the hole, and that the well construction grout (which gives off heat) has

cured for at least three days.

A temperature log is often very informative for holes several hundred or more feet deep, especially where deeper aquifers or fractures exist that are hydraulically not directly connected to a shallow aquifer. The equipment is easy to operate and is relatively inexpensive.

The thermistors may be quite fragile, and downhole breakage can occur if the borehole has edges that may catch the probe.

8.3-3.4 Self Potential (SP)

8.3-3.4.1 Principles of Operation

Electrochemical potentials are generated by interactions between ions in the borehole water and pore water in the borehole wall. The Self Potential (SP) method is a passive technique which measures these naturally-occurring voltage potentials in the borehole.

More importantly, in geologic environments in which groundwater enters the borehole through thin permeable zones, voltage potentials can also be generated electrokinetically (creating streaming potentials) when an electrolyte (groundwater) flows through a porous medium (rock or soil).

Zones of water gain or loss are often identified by a streaming potential on the log. Streaming potentials are generally negative and have a spiky, irregular character.

8.3-3.4.2 Applications

SP measurements are used for the following:

- o Identification of zones of water loss or gain (streaming potential)
- o Qualitative indication of clay content/determination of clay layers
- o Qualitative indication of water salinity
- o Rock type correlation/layer thickness

The SP log may be used in conjunction with the resistivity log to identify clay zones. Other logs, such as the neutron, gamma ray or temperature, can be interpreted with the SP to determine lithology and relative permeability. More than any other technique discussed herein, the SP method is not a stand-alone technique; it requires correlation with other logs.

8.3-3.4.3 Equipment

The downhole equipment for SP and resistivity logging includes a probe with lead or copper electrodes connected to the logging cable. The uphole

equipment includes the winch, electric control circuits, power supply, and recorder. Correct measurement of SP in a borehole requires that a grounding (reference) electrode or stake, which is electrically connected to the SP measurement system, be driven into the ground at least 25 feet from the borehole.

8.3-3.4.4 Field Procedures

Field procedures for electrical logging follow the same rules as most other logging methods. The probe is lowered to the bottom of the hole and measurements are made as the probe is pulled up the borehole. When making SP and single-point resistance measurements, it is important to have an effective ground electrode. In very hard or dry material it may be necessary to saturate the ground with water or electrolyte so that a good electrical connection exists between the electrode and the surface material.

8.3-3.4.5 Interpretation

The SP log can be interpreted to give qualitative information on clay content and permeability. To accomplish this, a line is drawn on the log at the maximum deflection of the SP as shown in Figure 8.3-4. A second line is drawn along the baseline. Deflections from the baseline indicate permeable zones. The magnitude of the deflection is proportional to the salinity of the water in a clay-free zone and proportional to the clay content in a clayey zone. If the borehole water has a lower ionic concentration than the formation water, the deflection will be negative; however, if the formation water has a lower concentration, the deflection may be positive.

Zones of water loss or gain can be detected as negative excursions from the baseline with a noisy or spiky, irregular character.

8.3-3.4.6 Advantages and Disadvantages

The SP curve commonly has reduced character in holes drilled with natural (formation) water because there is little geochemical activity between the borehole and formation waters. Deflections on the SP log can be very subtle in holes drilled with natural or moderately resistive water so that scales used in presentation must be changed to show greater detail. SP deflections can be reversed in areas where formation water has lower ion concentration than borehole water.

8.3-3.5 Fluid Resistivity

8.3-3.5.1 Principles of Operation

The resistivity of the formation fluid, which is the inverse of the conductance of that fluid, varies as the amount of major dissolved ions of salt compounds vary (i.e., fluids with high NaCl concentrations have high conductance and low electrical resistance). The measurement of fluid resistivity is accomplished by measuring the AC-voltage drop between two

closely spaced electrodes on a probe. This technique is the same as that discussed in Section 8.3-4.1 for formation resistivity in which a substantially greater spacing between electrodes causes the electrical field to easily penetrate the borehole environment and focus within the formation. Fluid resistivity is generally recorded in measurement units known as ohm-meters (times a constant that depends upon the manufacturer's design of the logging system).

8.3-3.5.2 Applications

Fluid resistivity logs are used to determine the general water quality with regard to total inorganic compound (namely salts) concentration. This geophysical method is commonly used to detect groundwater-conducting fractures in saturated rock environments. A procedure based on fluid resistivity (conductivity) logging has been demonstrated to quantify inflow rates from fractures into a borehole (Tsang, 1987). Because the SP and other resistivity-type logs are somewhat affected by borehole water quality, the fluid resistivity log can provide information to correctly interpret or quantitatively adjust other logs.

8.3-3.5.3 Equipment

Probes for fluid resistivity logging have two ring electrodes (four if multi-conductor winch-cable systems are used) spaced along a water intake tube that the borehole water flows through as the probe is lowered down the hole. Most groundwater investigative probes will fit into a 2-inch diameter hole, and are designed only for logging downhole. Electrical signals are transmitted to the standard surface electronics module, which converts these to counts per second as is done for most other log types. Some probes will measure both water temperature and fluid resistivity simultaneously. This arrangement is preferred as the water column in the borehole will not have been disturbed for either log type.

8.3-3.5.4 Field Procedures

The operation is very similar to that for temperature logging (i.e., slow downhole log recording). The tip of the probe housing the water intake tube must be kept open and clean. The log is begun with the probe end just under the water level in the well. The most sensitive span setting that will not cause full-scale deflection of the pen should be used, but commonly a conservative setting must be selected in the absence of knowledge of water chemistry variability in a particular logging environment. Dual recording systems (analog and digital) eliminate most problems with log insensitivity.

8.3-3.5.5 Interpretation

The fluid resistivity log is one of the more difficult logs to interpret in the absence of any groundwater quality analysis of borehole water and formation water (if different). The objective of fluid resistivity logging must be reconciled with the known (or unknown) condition of the borehole to derive reliable interpretation of general inorganic water

quality. Most important is the status of chemical conditioning of the borehole prior to logging, which usually relates to what fluids were used during the drilling process and what percent of the chemical substances were removed by development of the hole. Conditioning (intentional or unintentional) may greatly influence the degree of difference between in-situ groundwater chemistry and borehole fluid chemistry when the hole was logged.

If logging is to determine natural groundwater quality, the drilling fluid within the borehole and its invaded circumference must be removed or allowed to dilute to the natural concentrations with time prior to logging. In some cases, a return to natural borehole conditions can be knowingly achieved, and in other cases uncertainty will remain.

Interpretation is less complicated when the objective is to correct other resistivity logs, or to identify depths where the formation is actively yielding water to the borehole. In the first instance, the actual resistivity readings with depth are used without environmental interpretation. In the second case, recognition of groundwater inflow (or outflow) from the fluid resistivity log requires identification of trace excursions or offsets that are not the result of extraneous stresses occurring at the borehole. The reliability of fluid resistivity interpretations largely depends on what is known of borehole conditions and on the interpreter's experience.

8.3-3.5.6 Advantages and Limitations

Fluid resistivity logging provides a quick, relatively inexpensive means (as compared to extensive multi-depth water sampling) to qualitatively compare general inorganic water quality in various depth intervals of a borehole. It also may indicate depths where groundwater is moving into an open borehole and serve as collaborative evidence for such movement as suggested by a temperature or flowmeter log.

This technique requires that the hole be uncased, screened, or perforated over the depth interval of interest, and be filled with water to this level. The log must be made going downhole at a slow rate of speed. The most ideal situation for interpretation is that the drilling fluids be thoroughly flushed during development, and that enough subsequent time be allowed for chemical equilibrium to occur.

8.3-3.6 Inhole Flow Measurement (Flowmeters)

8.3-3.6.1 Principles of Operation

Several means of measuring the flow of water within a borehole using wireline geophysical equipment have been developed (Keys and MacCary, 1971, and Patten and Bennett, 1962). Three techniques have been well-documented: impeller flowmeter, tracer injection and monitoring and thermal flowmeter. The thermal flowmeter which measures vertical motion with high sensitivity is a newly tested instrument and, as of this writing (1988), is not widely available. Although it shows much promise for

accurately measuring very slow flow rates (Hess, 1982 and 1985), it is not discussed in this section.

Impeller flowmeters measure the revolutions of an impeller or vanes, mounted with its shaft parallel to the probe. This instrument is only capable of measuring flow velocities greater than about one to three feet per minute. Pulses are generated by the interaction between a very sensitive magnetic switch and a magnet placed on a shaft which rotates as a result of current flow. These pulses are sent up-cable to a standard rate-meter module, which registers each pulse on stationary time-drive or continuous depth-integrated logs. The speed of probe movement is critical to the log quality for the latter log type.

The tracer injection technique involves dispersing a "slug" of a tracer, such as salts, trivium, or fluorescein dyes (Driscoll, 1986), at a strategic depth in the borehole, and then monitoring its movement up or down the hole with respect to the exact recording of elapsed time intervals. The tracer hot-spot is assumed to move at exactly the same rate as the borehole water. Detectors located above and below the injection port on the probe are essentially fluid conductivity sensors.

These data are used to calculate borehole fluid velocities.

8.3-3.6.2 Applications

Inhole flow logs can be used to determine the rate of water movement between two permeable zones (or fractures) intersected by the open borehole, or opposite well screens or perforations. Rates of movement can be used to calculate a volume flow per unit time, and if the thickness and percent of total flow contribution of the permeable zone(s) are known, hydraulic conductivities can be determined (Schimschal, 1981). As complementary data, caliper logs for open-borehole applications are strongly recommended so as to derive the appropriate representative diameter of the segment through which flow was measured.

Flowmeter logging under conditions of surface discharge of borehole water (pumping or artesian flow) can provide data to interpret percentages of the total flow attributable to each permeable zone. This technique could be applied in competent rock holes to locate a dominant fracture that contaminants might follow and, thus, provide detailed information for discrete chemical sampling.

8.3-3.6.3 Equipment

An impeller flowmeter consists of a vane-type spinner mounted in a vertical axis position inside a strong cage on the bottom end of a probe. The diameter of the probe is smaller than the spinner, which is usually between three and four inches in diameter. The up-hole end of the probe connects to common cable heads. Single-conductor cable flowmeter probes are available. Surface electronics of most standard logging units can receive and process the pulses.

Tracer injector probes are relatively complex, as the tracer solution must be loaded and remotely ejected through small ports on the side of the probe. Because the direction of fluid movement in the borehole is commonly not known beforehand, probes having conductivity (resistivity) detectors both above and below the ejection port(s) should be used because they allow measurement collection while holding the probe motionless in the hole (a very desirable condition). In large diameter holes, the probe should be centralized. To obtain a visual field log, the analog recorder must have a built-in time-drive mechanism, or a computerized digital playback of conductivity readings versus time.

8.3-3.6.4 Field Procedures

Two primary options exist for operating the impeller flowmeter: depth-stationary recording and constant probe-speed recording. The depth-stationary method assumes that borehole water velocity is faster than the stall speed of the meter, either through 1) natural artesian flow out the top of the well, 2) induced flow through pumping of the well, or 3) natural flow between two or more separated permeable zones (a phenomenon known as "thieving"). To collect flow data, the flowmeter is positioned at selected depths, and a time-drive log is made at each for several minutes duration. The log on the right in Figure 8.3-5 shows a typical measurement.

The constant-speed technique is used when the flow in the hole is presumed to be near the impeller sensitivity speed and/or a large depth interval must be logged. Proper procedure requires downhole and uphole log recordings, both made at the identical probe speed. The left logs in Figure 8.3-5 show an example with a probe speed of 40 feet per minute. With speeds of this magnitude, rugosity of open boreholes may cause artificial anomalies if the probe bounces off or momentarily hangs on a protrusion (the operator must carefully watch the cable's action).

The procedure for obtaining tracer injection logs is less rigid; it depends upon the logging system being used, the rate of fluid travel, and if the direction of travel is known beforehand. The user is referred to Keys and MacCary (1971) for consideration of the various options.

8.3-3.6.5 Interpretation

Flow velocity is easily computed from stationary time-drive flowmeter logs by counting the number of pulses per unit time, and applying the calibrated flow rating for each individual probe. Feet per minute of travel is then used to compute the volumetric rate of flow, using the most accurate determination of average borehole (or casing) diameter.

Using the constant probe-speed technique, zones of increased impeller rotation on a log made in one direction and decreased impeller rotation in the opposite log direction are identified as having vertical flow. This phenomenon, as illustrated on the logs shown on the left side of Figure 8.10-5, can be seen to occur between the depth interval of 260 and 270 feet. Again, through calibration of the meter and by knowing the logging

speed, the velocity of flow can be computed.

Interpretation of trace injector logs is straightforward, assuming that the tracer plume passes a fluid conductivity detector during the monitoring period. The fluid velocity is computed as the distance traveled between the ejector and the detector (if the probe is held stationary as is normally the case) divided by the time span between ejection and the arrival of the peak conductivity recorded on the time-drive log. If the tracer substance has a specific weight much different than the borehole fluid, density corrections should be made. Radioactive tracers have been very successfully used in combination with gamma detectors installed in an ejector probe because they are detectable at very low concentrations. However, government regulation of radioactive tracers now is very stringent, discouraging their use.

8.3-3.6.6 Advantages and Limitations

Flowmeter logging can provide the best means to quantify natural movement of groundwater between two permeable zones in a borehole. It is the only direct method to determine the percent contribution of various permeable zones when a long section of an uncased bedrock hole, or long screened or perforated casing section, is pumped. Provided that the borehole fluid velocity is greater than 3 to 5 feet per minute, the impeller meter will detect the presence of fractures that are conducting water into or out of the borehole.

Use of flowmeters and other flow detection technologies to investigate groundwater movement is dependent on the existence of natural flow or the use of well pumps to create velocities greater than the detection limits of the technique. Impeller flowmeters must be calibrated in controlled velocity environments, and the meter must be rechecked if any significant wear or damage is suspected and if quantitative results are needed. The technique may not give good results in small diameter (2- to 3-inch) holes. If used in large diameter holes, a skirt should be attached to concentrate the flow past the impeller or sensors. Caliper logging of uncased holes is highly recommended prior to running in-hole flow tests, as not making diameter corrections may cause velocity errors to exceed 40 percent (Schimschal, 1981).

Trace ejector logging may provide reliable results at somewhat lower velocities, but this technique is difficult to use to investigate long sections of borehole. Both methodologies require relatively simple instrument controls and operator training.

Borehole flow logging is more time consuming than most other downhole logging.

8.3-4 FORMATION PENETRATING METHODS

8.3-4.1 Resistivity Techniques

8.3-4.1.1 Principles of Operation

Resistivity measuring devices (normal, single point and induction/EM probes) measure the electrical resistance of a volume of material around the borehole. These active techniques involve applying a current (AC or DC) to the formation and measuring the resulting potential field. The use of normal and/or single point techniques requires that the borehole be uncased and filled with a conductive fluid. The induction probe, which applies an electromagnetic field to induce currents in the formation, is employed when a current cannot be applied directly, such as in air-filled or PVC-cased holes.

The single-point resistance probe is the most commonly used resistivity device. It consists of a single lead electrode connected to a power source and voltage meter (Figure 8.3-6). A constant current is applied to the electrode and the voltage between the electrode and surface ground, which basically varies with earth resistance, is measured in the same manner resistance is measured with a volt-ohm meter. The actual property measured with the single-point device is resistance, in ohms. Resistivity is a volumetric quantity expressed in ohm-meters.

The normal device, also called the two electrode system, employs the use of two electrodes on a probe, spaced a selected distance apart (see Figure 8.3-6). The lower electrode is used to apply a constant current to the formation. The upper electrode is used to measure the potential field at that point. The electrode spacing determines the depth of investigation of the normal tools. The depth of investigation into the rocks surrounding the borehole is approximately equal to about half the electrode spacing. Common spacings are 16, 32, and 64 inches. Closer spacings may be used to advantage in slotted PVC casing, with minor adjustments.

When borehole conditions (i.e., air or foam filled holes or in holes cased with PVC) prevent a current from being applied directly to the formation, as is the case for normal and single-point methods, an electromagnetic probe, also known as the induction technique, may be used. The induction probe is essentially the same as the surface terrain conductivity instrument described in Section 6. A lower transmitter coil produces an electromagnetic field which generates a ground loop (circular currents around the borehole). The secondary field created by the ground loop in the rocks and fluids surrounding the borehole is measured by the upper coil, and is proportional to the conductivity of the material between the coils.

8.3-4.1.2 Applications

Resistivity logs are used to determine:

- o Water saturation
- o Porosity (when the conductivity of formation water is known)
- o Clay presence
- o Basic water quality (i.e., conductivity due to salts - when the formation porosity is generally known)

Generally, when these parameters are to be determined, a log suite consisting of gamma ray, SP, acoustic velocity (to be explained later in this section), and resistivity is run. Also, the resistivity and induction method can often be used to identify contaminated zones, if the contaminants have an electrical conductivity significantly higher or lower than the hydrogeologic environment and an adequately high concentration is present.

8.3-4.1.3 Equipment

The downhole equipment for single-point resistance and resistivity logging includes a probe with lead or copper electrodes connected to the logging cable. The uphole equipment includes a winch, electronic control circuits, power supply, and recorder. Single-point resistance logging, which utilizes only one probe electrode, requires that a grounding electrode or stake be driven into the ground at least 25 feet from the borehole.

Two induction instrumentations are available for groundwater investigations, with slightly different configurations. A stand-alone portable unit is commercially available which focuses the electromagnetic field into the formation beyond the walls of the borehole. This unit includes a two-coil probe; a 9-mm diameter, seven conductor logging cables; uphole electronics module; power supply (12 VDC); and an analog or digital recorder. The other configuration for the induction logging equipment is a standard multi-conductor probe that is compatible with truck-mounted logging equipment.

8.3-4.1.4 Field Procedures

Field procedures for electrical logging follow the same rules as most logging. The probe is lowered to the bottom of the hole and logs are made as the probe travels up the borehole. When making a single-point resistance log, it is important to have an effective ground electrode. In very hard or dry material it may be necessary to saturate the ground with water or electrolyte so that a good electrical connection exists between the electrode and the surface material. The logging cable must be electrically insulated for a distance of 5 times the electrode spacing when running normal resistivity logs. Logging speeds can be as high as 30

feet per minute for electric logs without losing log quality.

A variable-resistance decade box should be used during each day of field logging to calibrate the system's response output in ohm-meters.

8.3-4.1.5 Interpretation

Resistivity measurements can be used qualitatively to interpret porous water-filled zones or fracture zones. Usually, these zones have lower resistivities than adjacent non-porous or non-fractured zones. After these low resistivity zones are identified, they should be compared to the SP and gamma-ray logs to verify that they are not clay zones which also have low resistivity. The single-point resistance probe is especially sensitive to individual open fractures with apertures greater than about 0.1 foot.

Porosity can be estimated from resistivity logs if the resistivity of the formation water is known. Formulas to calculate formation porosity can be found in Keys and MacCary (1971). For example, formation porosity for sandstone can be determined graphically from Figure 8.3-7.

Qualitative estimates of water quality can be made from resistivity logs in clay-free zones. As specific conductance increases, the resistivity will decrease, assuming the porosity and lithology are constant. Thus, brackish and salt-water aquifers will show lower resistivity than fresh-water aquifers of similar porosity and lithology. Keys and MacCary (1971) and Kwader (1982) describe methods of estimating water quality from electric logs. The methods employ the use of mathematical expressions or cross-plots to relate properties such as formation resistivity factor, fluid resistivity, porosity, cementation factor, specific conductance, and dissolved solids.

When used with the SP and gamma-ray logs, the resistivity log can give valuable information concerning lithology, water content, and groundwater quality. Because electrical current passes through soil by way of water in the pores, it is possible to locate the top of the saturated zone using this method. If a single-point or small-spacing resistivity probe is used, the capillary fringe can often be identified.

Resistivity values are not unique for specific lithologies. However, clays usually have low resistivities and most non-fractured, unweathered igneous and metamorphic rocks have high resistivities. Fresh-water saturated sands normally have resistivities significantly greater than clays. Fine-grained sands and silts commonly have lower resistivities than coarser sands and gravels. In coastal environments, the resistivity log is used to discriminate the higher resistivity fresh-water aquifer from the lower resistivity brackish or saline sea-water aquifer.

8.3-4.1.6 Advantages and Disadvantages

Borehole electrical methods are rapid, repeatable, and well-documented techniques that require simple equipment and all can be run in two-inch ID

holes. They are effective methods for determining the presence of clay layers and water quality.

The primary disadvantage of the electrical methods is that (with the exception of induction/electromagnetic techniques) they require water-filled uncased boreholes. Another disadvantage is that these methods generally require a fracture with an aperture greater than 0.1 foot.

The induction/electromagnetic probe is effective in low to moderate resistivity formations, and provides resistivity data under conditions where other techniques cannot be applied (air-filled holes and PVC-cased holes). A disadvantage of the induction/electromagnetic technique is that it has poor vertical resolution (cannot resolve layers less than 2-3 ft thick) and gives unreliable data in high resistivity formations.

Resistivity and SP measurements are very sensitive to the resistivity of the drilling fluid. If drilling fluid is highly resistive and the borehole diameter relatively large, thin beds and more resistive beds will not be detected, as most of the current is forced to travel along the borehole walls (Kwader, 1982).

In glacial terrain, boreholes must be cased with PVC or steel. Use of these materials usually precludes single-point, normal resistivity and SP methods, although they can be run in the screened interval of PVC-cased wells. Care should be taken to ensure the integrity of the borehole so that expensive logging probes are not lost by collapsing sections of the borehole.

Electrical methods provide calibrated, quantified results in low to moderate resistivity, water-saturated rocks and soil, such as clays and saturated sand and gravel. Electrical methods give only qualitative to semi-quantitative results in high resistivity materials, such as unfractured granite or dense silty till.

8.3-4.2 Acoustic (Sonic) Methods

8.3-4.2.1 Principles of Operation

Acoustic borehole methods are a group of active techniques that use sound waves to measure the acoustic properties of the soil, rock, and fluid near the borehole. The velocity with which sound propagates through the materials, and/or the strength of the signal at the receiver, are evaluated in conjunction with other geophysical techniques (i.e., SP, Resistivity) to determine the type of the material penetrated. The techniques include:

- o Velocity logging
- o Amplitude logging
- o Wave-form analysis

- o Acoustic televIEWER

The most common of these techniques is velocity logging. The acoustic methods can be used in open or cased holes. A fluid-filled hole is usually required to transmit the sound wave to the formation. Dry hole acoustic probes are available, but have limited applications. A discussion of basic acoustic logging methods can be found in Labo (1987) or Keys and MacCary (1971). More detailed information on the acoustic televIEWER can be found in Paillet (1980) and Zemanek and others (1968).

In its simplest form, the acoustic velocity logging technique uses a sound-wave source generator and a receiver mounted on a probe at a fixed distance from the generator (Figure 8.3-8). The generated sound wave is propagated through the borehole fluid and refracted into the formation. A portion of this acoustic energy travels parallel to the borehole and is refracted back to the receiver. Electrical circuits are used to measure the transit time for the sound waves to travel from source to receiver. These data are presented on the log as travel time, recorded in microseconds per foot. Many acoustic velocity logging systems are designed with two or more receivers and two sound-wave generators to minimize the following borehole effects:

- o Travel time through borehole fluid
- o Irregularities in borehole size (indicated by caliper logs run in uncased holes)
- o Orientation of the probe in the hole

Multiple-receiver probes (see Figure 8.3-8) measure travel time by taking the difference between the first arrival of the sound wave from the near and far receivers. Some logging systems are also equipped to record the strength, or amplitude, of the first arrival, usually in millivolts. These acoustic logging systems contain an oscilloscope which allows the entire wave train to be observed while logging. The wave train can also be photographed or recorded digitally so that a complete analysis of all portions of the wave may be performed.

The acoustic televIEWER is an elaborate probe that contains one or more sound-wave source generators and receivers mounted radially on an internal rotating mechanism (Figure 8.3-9). The rotating mechanism is powered by a small electric motor and contains a magnetic orientation device used to tie the acoustic measurements to compass directions. As it rotates, high frequency sound waves are generated and reflected off the borehole and back to the probe. Receivers, located coincident with the sound-wave generators, measure the amplitude of the reflected wave and send the information uphole. The wave amplitude data is combined with the simultaneously collected probe orientation and depth information to produce an uncoiled 360-degree acoustic image of the borehole (Figure 8.3-10).

8.3-4.2.2 Applications

Acoustic velocity measurements can be used to determine

- Porosity (for known lithology)
- Lithology (determined in conjunction with other logs)
- Rock strength
- Fracture location
- Validity of seismic refraction interpretations

Porosity can be determined from the acoustic velocity log if the formation compensation is known and is clay-free, consolidated (grains cemented together) and fluid-bearing. The porosity is calculated from the relationship established by Wyllie (1963) which involves transit times through the rock and the pore fluids.

The accuracy of the calculated porosity is dependent on the accuracy of the matrix identification. Because the acoustic travel time varies with porosity and rock composition it is a non-unique response. Lithology can only be confirmed if other logs such as the neutron, gamma-gamma or natural gamma are used for verification. The acoustic travel-time log can be used to verify seismic model layers determined by the seismic refraction method (Section 3).

Matrix travel times for sedimentary rocks (shale, sandstone and limestone) are well documented and vary within known limits. Matrix travel times for igneous and metamorphic rocks vary considerably and are not well defined by the present literature. For this reason it is recommended that the interpretation of the acoustic velocity log be limited to identification of relative changes in porosity in igneous and metamorphic rocks, unless detailed information concerning rock type or seismic velocities are available. Dobrin (1976) provides a table of velocities for various sedimentary, igneous and metamorphic rocks (Table 8.3-2).

Relative rock strength can be estimated from acoustic travel-time data in zones of similar rock type. Increases in travel-time can indicate zones of weathering, alteration or fractures, which also have higher porosity than rock outside such zones.

The acoustic amplitude log can be used as an indication of conditions at the edge of the borehole, such as cement bonding quality between steel casing and the formation. If there is a good bond, the acoustic amplitude is high. However, if there is a gap caused by partial grouting, the signal from the formation will be weak (attenuated) and show as a low-amplitude zone. Low amplitude can also be an indication of fractures, unconsolidated or soft material, weathering, or mineral alteration in uncased holes.

The full waveform acoustic log records the complete acoustic wave so that various components of the wave may be identified. These components include the arrival times and amplitudes of:

- Compressional waves
- Shear waves
- Tube waves

Shear- and tube-wave data can be used to locate fractures and estimate permeability. The shear-wave and tube-wave information also is used to calculate engineering properties used in the design of remedial structures or systems. These engineering properties are:

- Bulk modulus
- Shear modulus
- Poisson's ratio
- Young's modulus

The reader is referred to Dobrin (1976) for a complete discussion of the calculation of these properties from seismic and acoustic log data.

The acoustic televIEWer is used primarily to identify and measure the strike and dip of fractures. However, it can also be used to identify other borehole and rock conditions such as hole enlargements, hole obstructions, rock breakouts, foliation, and zones of weakness due to weathering or alteration.

8.3-4.2.3 Equipment

Acoustic logging methods require relatively complex electronic systems and instrument controls to produce acoustic logs. Sophisticated timing and measuring circuits are used to pulse the sound-wave generators and turn the receivers on and off. An oscilloscope is used to visually inspect the quality of the sound wave as it is transmitted and received. All of these components are contained in the surface electronics package. The probe contains the sound-wave generators and receivers. A specially designed camera may be necessary to record the full waveform acoustic log.

8.3-4.2.4 Field Procedures

The acoustic televIEWer logs must be run at very slow probe speeds, commonly four feet per minute. Calibration of acoustic surface electronics is generally performed internally by passing a reference signal through the circuits. There are no calibrations needed for acoustic probe electronics apart from the surface system calibration. For quantitative velocity determination, it is best to calibrate the system by correlation with velocities determined by core tests or a seismic

refraction survey.

8.3-4.2.5 Interpretation

The porosity value calculated from the acoustic velocity log represents the primary (intergranular) porosity only. Secondary porosity created by vugs, dissolution, and fractures is not detected by the acoustic velocity method because the sound wave travels along the fastest path, which is through the rock rather than the fluid. If the total porosity from the density or neutron log is compared to the primary porosity from the acoustic velocity log, the amount of porosity due to vugs and fractures can be determined.

When the amplitude of the received sound wave is low due to inhomogeneities in the rock (fractures, vugs), the first arrival of the sound wave may not be detected because it is below the detection limit of the probe. Later arrivals with higher amplitudes trigger the detector and show as very long travel time on the log. This phenomenon is called "cycle skipping." The log usually looks very spiky and irregular when cycle skipping occurs. Cycle skipping may indicate vugs, fractures or weak rock.

Acoustic travel times for specific depths can be plotted against gamma-gamma, neutron, or natural gamma count rates at corresponding depths to define rock-type groups (Figure 8.3-11). This technique, called cross-plotting, is very informative, especially when combined with core or other geologic data.

Full acoustic waveform interpretation is similar to vertical seismic profiling (VSP) interpretation; therefore the reader is referred to Section 8.3-4.4 for a more complete discussion.

Interpretation of acoustic televiewer images (logs) is somewhat subjective unless borehole wall character is evidenced on other logs. The basic premise is that strong signals from smooth borehole walls of competent rock appear as bright areas on the log, whereas fractures, soft seams and weathered rock appear as dark areas.

8.3-4.2.6 Advantages and Disadvantages

The acoustic probes are advantageous because they provide perhaps the most accurate information concerning fracture location, geometry and characterization, and need not require confirmation by other log types for some purposes.

The primary disadvantage of acoustic velocity techniques is their relatively high cost and complexity, and their limited value in cased holes penetrating unconsolidated materials. The acoustic tools must be run in water-filled holes so that the sound wave is effectively transmitted to the borehole walls. However, special receivers are available for use in dry holes, but they must be clamped to the side of the borehole, thus preventing continuous logging of the hole.

The acoustic televIEWer is not readily available among geophysical contractors, because it is an expensive, relatively specialized probe. Furthermore, the quality of the log, and thus reliability of interpretation, depends strongly on the operator's experience and ability to set the proper acoustic focus. As major changes in the borehole diameter occur, refocusing is commonly required.

The reader is referred to Zemanec and others (1969 and 1970) or Taylor (1983) for a complete discussion of the interpretation of the technique.

8.3-4.3 Nuclear (Radiation) Methods

8.3-4.3.1 Principles of Operation

Nuclear logging methods include both passive (natural gamma-ray) and active (gamma-gamma and neutron) techniques. These techniques are used primarily for the determination of porosity and lithology. Most nuclear methods employ the use of geiger tubes or scintillation crystals to detect the intensity of radioactivity. The detector emits photons (flashes of light) when struck by radioactive particles (neutrons and gamma-rays). The photons are converted to electrical pulses and sent uphole to counting and timing circuits, where a surface electronics module converts these pulses into counts per second. All nuclear logs can be run in open or cased holes, and in dry or water-filled holes.

8.3-4.3.1.1 Natural Gamma-ray Log

The natural gamma-ray log is a measure of the naturally-occurring gamma radiation in the formation. Natural gamma radiation is produced by the radioactive decay of potassium, thorium (Th) and uranium (U) atoms. Clay minerals show high gamma ray readings because they commonly contain potassium in their chemical structure. Clay minerals also promote the adsorption of positive ions, such as Th⁺ and U⁺, because of their open crystal lattice structure and net negative charges. Thus, the natural gamma log serves as a reliable clay indicator in those environments where non-clay beds do not contain radioactive minerals. However, some granites and their weathering products are also rich in radioactive minerals, and also will give high gamma-ray counts.

8.3-4.3.1.2 Gamma-gamma Log

Gamma-gamma logging uses a solid, encapsulated radioactive source (generally cesium-137 or cobalt-60) mounted 10 to 35 inches from the detector to bombard the formation with medium-energy gamma-rays. The gamma-rays are scattered as they collide with the electrons of the material in the formation. With each collision, an individual gamma particle will lose some of its energy until it reaches a low energy state and is absorbed by an electron. The probe measures the number of gamma rays that are reflected back to the detector. The number of electrons detected by the instrument is inversely proportional to the density of the formation evaluated. Therefore, very dense formations, which have high electron densities and will reduce gamma energy quickly, will cause fewer

gamma rays to reach the detector, while less dense formations will exhibit higher gamma count rates. If the formation lithology (and density) are known, variations of density measured can be attributed to changes in porosity.

8.3-4.3.1.3 Neutron-epithermal-neutron Log

The neutron-epithermal-neutron log is used to determine porosity as a function of formation hydrogen content. The basic assumption in the calculation of porosity using this method is that all pore (void) spaces in a formation are water filled. This survey method can be employed below the water table to measure porosity and above the water table to indicate relative moisture content in the unsaturated zone.

The neutron probe is similar in design to the gamma-gamma probe, except an americium-241 beryllium radioactive source is installed. This source emits fast neutrons which collide with atoms in the formation and are slowed down. The most effective atom in slowing down fast neutrons (because of its similar atomic mass) is the hydrogen atom, which is a major constituent of water. When neutrons reach a very low energy level they are captured primarily by hydrogen atoms, and gamma energy is released. Detectors are designed to detect (count) either neutrons or gamma photons released by neutron collisions. The counting rate for both types of detectors is inversely proportional to the hydrogen content of the formation. The instrument detection results are converted to porosity.

Although a neutron log cannot be used for measuring porosity above the water table, it is very useful for measuring changes in the moisture content.

8.3-4.3.2 Applications

Nuclear techniques are used primarily to identify the presence of clay, correlate lithologies, and determine porosity. These techniques are most valuable if the probes are calibrated with appropriately-constructed field standards of known properties, and, therefore, accurate densities and porosities can be determined. The gamma-gamma and neutron radiation logs provide a record of count rate, which must be scaled with a calibration rating curve after dead-time corrections are applied (moderate to high count rates only) to provide porosity values.

Natural gamma and neutron logs can aid in the identification of perched aquifers, especially when used with a resistivity technique. Opposite a perched aquifer the resistivity is low; the neutron log would show increased water content, and the natural gamma should confirm the perched zone to be non-clayey materials. As the resistivity and neutron probe responses may be similar for clay and water-saturated sands due to water molecules bound to the structure of clay minerals, the natural gamma log is critical for correct interpretation.

8.3-4.3.3 Equipment

The three nuclear techniques use very similar surface and downhole equipment. While a few nuclear logging systems use the same probe and detector for all three methods, with only the source and source-to-detector spacings changed, most logging systems employ the same probe for natural gamma and gamma-gamma, but a different probe for neutron. The uphole electronics consists of a counting and timing circuit for recording data in counts per second. A more complex electronics package is required for directly recording porosity during gamma-gamma or neutron logging.

The gamma-gamma and neutron methods require the use of a solid, encapsulated, chemical radioactive source. Although these sources are relatively small, they present a safety concern for the operators of the equipment. The sources are regulated by the Nuclear Regulatory Commission (NRC) and must be licensed. Use of licensed sources is limited to those persons who have proper training and have obtained NRC certification in nuclear materials handling and safety. These sources are transported and stored in locked, shielded carrying cases and are secured to the probe only during actual logging.

Another aspect of safety is the use of active sources in uncased, loose formations. The potential for getting a probe stuck in the hole often is significant when borehole walls consisting of unconsolidated soils are unstable. It is recommended that no probe with a radioactive source be run in an uncased hole in an unconsolidated formation.

8.3-4.3.4 Field Procedures.

Nuclear logging methods follow the same general field procedures as other logs. One notable difference is that radioactive sources used with the density and neutron techniques are installed using a site-specific field routine that minimizes radiation doses to the operator. Also, log quality and repeatability are enhanced if a probe decentralizer is used in hole diameters of 8 inches or greater. Probes are calibrated at the site using either a source of known strength (field standard) to check detector response or a piece of material with known physical properties to check total probe response.

For uncased holes in competent rock, a caliper probe is always run before the nuclear probes because of the serious consequences of getting a radioactive source stuck in the hole.

Radiation probes are generally run at a slower speed (10-15 ft/min) than most other probes so that the count rates can be averaged over a longer period of time, thus reducing the statistical variability and making the logs more repeatable.

8.3-4.3.5 Interpretation

None of the radiation logs have a unique count rate response to individual lithologies (see Figure 8.3-12); however, within a single geohydrologic

environment, any given geohydrologic unit (layer) generally shows a consistent response. This aspect gives these logs much value in correlating lithology between well sites.

Natural gamma logs respond primarily to the amount of potassium, and secondarily to the amount of thorium and uranium isotopes in the formation. As potassium is a major component of most clay minerals, the natural gamma log is generally considered to be a clay-content log.

Other minerals that can cause high gamma counts include:

- Feldspars (high potassium) - found in many granites and other light-colored igneous and metamorphic rocks
- Micas (high potassium; may contain thorium) - found in granites
- Hornblende (can contain thorium and uranium) - a common accessory mineral in granites and some metamorphic rocks
- Uranium minerals in granites and sands

Sometimes, a natural gamma log will show high radioactivity opposite fractures or fractured zones in bedrock. These spikes are usually due to uranium-rich mineral precipitates lining the fracture walls, but small excursions on the log may represent clay-filled fractures.

Natural gamma log responses should be cross-examined with the SP and one of the resistivity log types to confirm rock type. Fractures can usually be identified with the single-point resistance log.

Neutron logs will respond to water bound in the crystal structure as if it were pore water. It is important to check for the presence of clay with SP or natural gamma when using the neutron log to determine porosity. The neutron probe is affected by borehole enlargements and high chloride content. Under these conditions, the neutron log should be used only as a general indicator of porous zones.

Rocks and glacial sediments show an extremely wide range of bulk densities (the combined density of rock, fluid, and air). If the lithology is known, a reasonable estimate of porosity can be made by using published relationships.

The density log can also be used to detect voids and channeling in grout behind casing. Voids and channels in grout may provide pathways for transport of water and contaminants between layers.

When analyzed together, the gamma-gamma and neutron logs commonly indicate zones of formation washout that exist behind the well casing, caused by the drilling process. Washouts and aquifers may give a similar response on these logs, and commonly the natural gamma log must be consulted.

8.3-4.3.6 Advantages and Disadvantages

Nuclear techniques work well in a wide variety of borehole environments including cased (PVC or steel) and uncased holes in saturated and unsaturated formations. Their primary advantage is that, when properly calibrated, these logs give estimates of porosity and lithology that are consistent with independent field and laboratory test results. The porosity and lithology measurements are made in-situ at accurately known depths, thus reducing cost and time involved in comparison to core sampling and aquifer test pumping.

Most of the probe response in nuclear logging is from the first six inches to one foot of the formation surrounding the borehole. Sometimes this zone may be very disturbed, due to drilling and completion procedures that may force drilling fluids into pore spaces near the borehole or alter the compaction of loose materials. If large augers are used and a small diameter well is installed, most of the radiation response is from the gravel pack (filter sand) or backfilled material. In such cases a false indication of formation properties may be obtained. The best hole conditions result from driving casing or open-hole drilling in competent rock.

Hole diameter variation and rugosity of the borehole walls affect all nuclear logs to some degree, depending on source strength and the chosen spacing between source and detector. Gamma-gamma density logs made with a weak radiation source and short spacing may be severely affected, misrepresenting true formation density. Neutron probes have a lesser sensitivity to the same conditions, while natural gamma logs generally are not significantly affected unless a large void or washout is present. Caliper logging in open holes provides data for correcting radiation logs for hole diameter variations. However, quantitative determination of density and porosity opposite washouts in cased wells is not possible.

Radioactive sources are regulated by the NRC and must be licensed. The use of geophysics tools employing radioactive sources is restricted to only those persons who have NRC certification. The consequences of losing a radioactive source (i.e., by being unable to retrieve a downhole source/probe) is serious and costly.

8.3-4.4 Vertical Seismic Profiling (VSP)

8.3-4.4.1 Principles of Operation

Vertical Seismic Profiling (VSP) is a borehole seismic survey method used to detect and characterize open fractures within rock. The VSP method was developed in the petroleum industry and has recently been applied to hydrogeologic characterization for environmental studies. This method provides a three-dimensional image of subsurface velocities and geologic structure, utilizing an array of seismic borehole geophones (motion sensitive sensors) or hydrophones (pressure sensitive sensors) placed in a borehole at the depths of interest. The technique is illustrated schematically in Figure 8.3-13.

The VSP technique uses a seismic source, placed at the surface some distance away from the borehole to generate seismic waves, which travel through the ground and are detected by the geophones in the borehole. These waves consist of compressional waves (P waves) and shear waves (S waves). Figure 8.3-13 shows a schematic representation of the seismic wave received by the geophones.

When a fluid-filled fracture, which intersects the borehole, is squeezed by compression from a seismic wave, a pressure pulse known as a tube wave is generated in the borehole. The tube wave is detected by the geophones as the pressure pulse is propagated upward and downward in the borehole. The size (amplitude) of tube waves generated by a permeable fracture depends on the hydraulic conductivity of the fracture, elastic properties of the rock, fluid properties, and borehole radius. High permeability fractures yield large amplitude tube waves. Tube wave amplitudes are generally much larger than those of compressional waves (see Figure 8.3-13).

8.3-4.4.2 Applications

A particular application of this technique is the detection of open, water-filled fractures which are intersected by a borehole (Levine and others, 1985). Compressional, shear, and tube waves can be used to characterize the fractures in terms of depth, attitude, and hydraulic conductivity.

When the formation and fluid properties are known, tube wave amplitudes can be used to determine the hydraulic conductivity (K) of a fracture. The K value is determined through the comparison of compressional wave pressure amplitude to that of the tube wave as measured by the hydrophone positioned closest to the fracture depth. The use of the nearest hydrophone removes the effects of the source as well as the recording system response.

If desired, the lateral extent of the fracture can be delineated by moving the surface source away from the borehole and observing changes in the transmitted and reflected compressional and shear waves (see Figure 8.3-14). Because the compressional and shear waves scatter, attenuate, reflect, and refract at a fracture zone, computer ray-tracing methods can be used to image the geometry of the fracture. Of particular note is the significant attenuation of shear wave energy through a fracture zone or other low velocity zone.

8.3-4.4.3 Equipment

A string of hydrophones or unclamped geophones are used in the borehole to detect the tube waves. The hydrophone responses are transmitted to a surface recording unit. This surface unit should consist of digital recording instrumentation capable of timing in the range of tens of microseconds and with playback capability for later analyses.

The VSP technique generally uses conventional seismic sources (e.g., weight drop, explosives, Betsy seisgun) placed on the ground surface at appropriate locations or within nearby shallow borings. The energy source with the highest frequency content consistent with the attenuation characteristics of the earth materials at that location should be used.

8.3-4.4.4 Field Procedures

The following field procedures allow fracture characteristics, primarily depth, length, and orientation, to be determined.

Surface energy sources are arranged in a radial pattern around the hole and placed at various distances from the borehole. Receivers are placed within the uncased bedrock segment of the borehole. Each source location is detonated individually, with data being stored digitally for each geophone for each shot. After all seismic recordings are made, the sensor array may be raised or lowered in the borehole to span deeper or shallower unmonitored segments. Sensor spacings are directly related to the degree of accuracy with which individual fractures or fracture zones need to be defined. Wide sensor spacings (25 to 50 feet) are useful in identifying depths to zones of fractures; closer sensor spacings (5 to 10 feet) may identify individual fractures. Additional data are recorded until the entire water-filled section of the borehole has been surveyed.

The data are stored on magnetic tape or disk for further computer processing, such as amplitude, frequency and particle motion analysis. A complete display of VSP data from the top to the bottom of a borehole can also be made using the stored data.

8.3-4.4.5 Interpretation

Tube waves indicative of permeable fracture zones are often readily apparent on the seismic recordings. By using an appropriate X-Y data display (individual sensor seismograms with time along one axis and depth along the other axis), the depth at which the tube waves originate can be determined within a few feet if closely-spaced sensors are employed. The orientation of the fracture can be approximated by analysis of the tube-wave to compressional-wave amplitude ratio. Geophone records from energy sources located at the same distance, but different angles, around the borehole are used for this analysis. Because of the qualitative nature of the analysis, results are presented in terms of shallow-, moderately-, or steeply-dipping fractures. Analysis of the amplitude ratios will define the strike of steeply-dipping fractures to within ± 10 degrees, and that of moderately-dipping fractures to within ± 15 to 20 degrees. The more data available from different azimuths, the better is the fracture orientation definition.

The continuity and extent of fractures can best be determined if multiple boreholes are investigated. If a fracture intersects two boreholes, the continuity of the fracture can be determined through computer modeling and imaging. Borehole-to-borehole seismic methods can also be used to establish fracture continuity through the use of guided wave technology.

(i.e., energy generated in the vicinity of permeable fractures in one borehole and high-amplitude, high-frequency seismic waves recorded in an adjacent borehole).

The tube-wave amplitude is generally influenced by the hydraulic conductivity of the fracture. Other factors such as the physical properties of the medium surrounding the borehole, the frequency of the seismic waves, the properties of the fluid filling the borehole, and the radius of the borehole may also affect the amplitude. The amplitude ratio (tube-wave to P-wave) versus frequency is the key relationship used to establish the hydraulic conductivity of a fracture zone. A set of curves can be generated showing amplitude ratio versus frequency for different hydraulic conductivity values. A set of such curves is shown on Figure 8.3-15. The determination of hydraulic conductivity values by the VSP technique has been verified through correlation with permeability test data.

8.3-4.4.6 Advantages and Disadvantages

Vertical seismic profiling yields clear and definitive results for identifying permeable fractures intersecting a borehole. As numerous studies have shown, some fractures detected by other logging techniques, such as acoustic logging, borehole televiewer, electrical and caliper logging, are not permeable and are not fluid conductive.

The VSP technique has been used in all types of rock with varying degrees of success. The greatest successes for fracture and hydraulic conductivity objectives have been achieved in igneous and competent metamorphic rocks, which appear to have rather distinctive faulting and fracturing zones. Its use in sedimentary rocks and weathered metamorphic rocks, which may have extensive zones of permeable materials, has been less successful.

VSP results away from the borehole are limited to the seismic-ray paths from the seismic source to the detectors. This procedure may, or may not, be sufficient to determine the lateral extent of a fracture away from the borehole and provide control on the attitude of any permeable fractures identified.

The VSP technique requires relatively sophisticated equipment when compared with many of the other borehole techniques. It is also time-consuming and, thus, relatively expensive.

8.3-5 GLOSSARY

Active technique - A technique in which a stress is applied to the material under study and the resultant response is measured. Stresses can include electrical current, sound waves, or neutron or gamma ray bombardment.

Calibration - The process wherein the zero and sensitivity of the logging circuitry is set so that the recorded measurements will be accurate with

respect to industry-standard units of measurement for a specific log-type (i.e., grams/cubic centimeter for rock density).

Dead time - In radioactive logging, the length of time (usually measured in microseconds) required by a logging system to recover from counting one disintegration event in order to count (record) the next event. Events occurring during dead time are not counted.

Formal depth-registered log - A geophysical log recorded on graph paper or digitally in which accurate downhole depths are simultaneously and systematically registered opposite corresponding log responses, and detailed logging run information is recorded in a log header.

Lithology - The physical character and composition of a rock, implying a specific rock or soil type.

Measuring point - The point, on a probe, where the reading is taken (e.g., the tips of the caliper arms; the detector on a gamma-ray probe).

Non-unique response - Response that is not unique to a specific rock characteristic. As examples, several different rock types exhibit low gamma-ray counts; or water-filled fractures and clay layers both have low resistivity values.

Passive techniques - A technique which measures properties inherent to the material. Examples include SP, gamma-ray, temperature.

Probe - The downhole electronics and detecting/measuring apparatus of the logging system, usually encased in a stainless steel jacket.

Radioactive decay - The transformation of an unstable isotope into an isotope of another element, resulting in a loss of energy and the emission of radiation (e.g., alpha or beta particles, neutrons and/or gamma rays).

Reference elevation - The aboveground elevation which is designated as a common point for referencing all measurements for correlative purposes (commonly, ground surface or top of casing).

Resolution (vertical) - The capability of a logging system to distinguish geophysical changes between closely spaced (thin) lithologic units.

Rugosity - The degree of roughness or irregularity of the borehole wall, which affects some log types.

Total depth (TD) - The deepest point in the boring as determined by accurate measurement, in this instance geophysical logs. Discrepancies commonly occur between total drilling depth and total depth from geophysical logs, due to filling of the bottom of the borehole from caved material or to cable stretch (very deep holes only).

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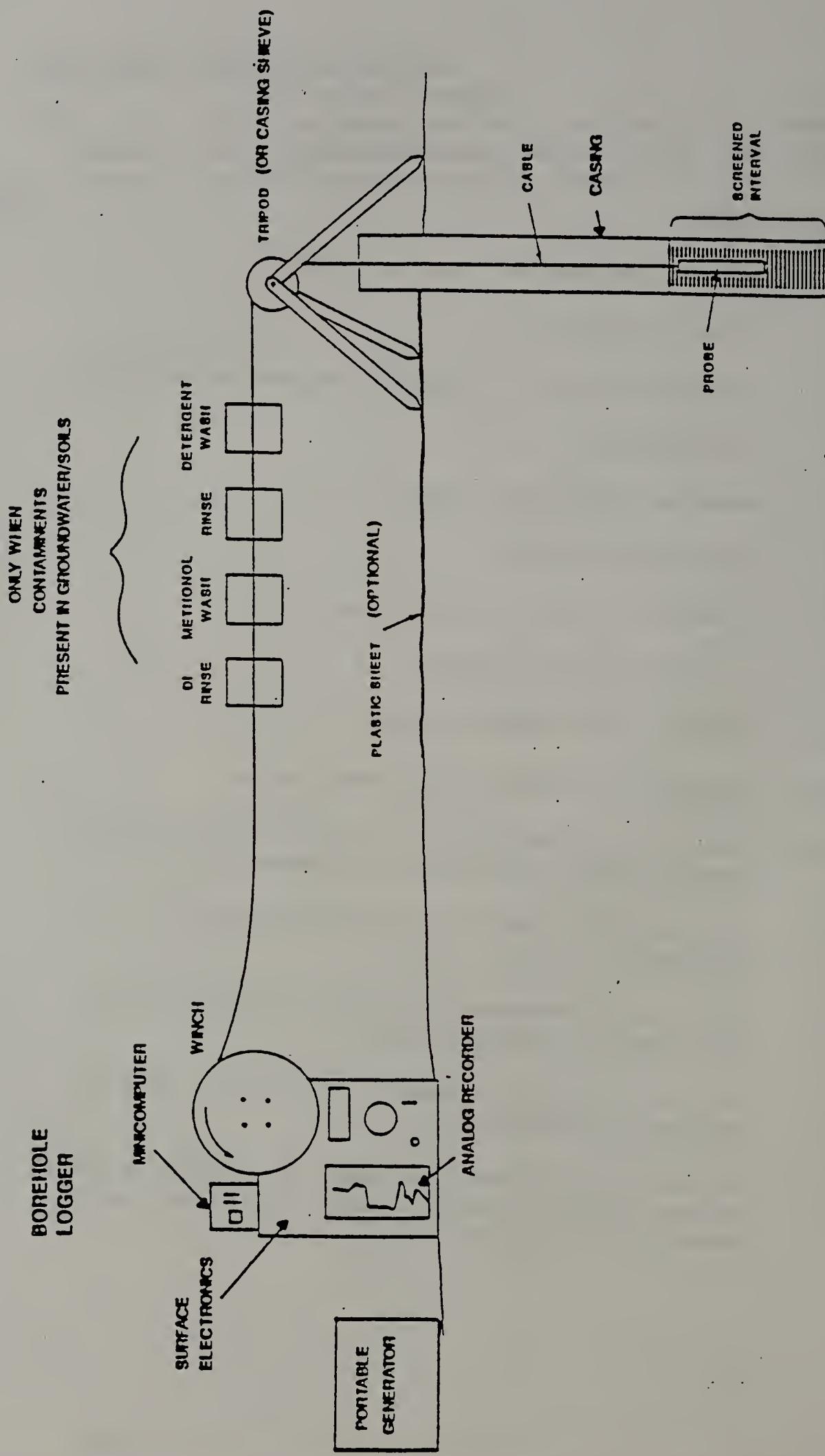
SECTION 8.3
BOREHOLE GEOPHYSICS

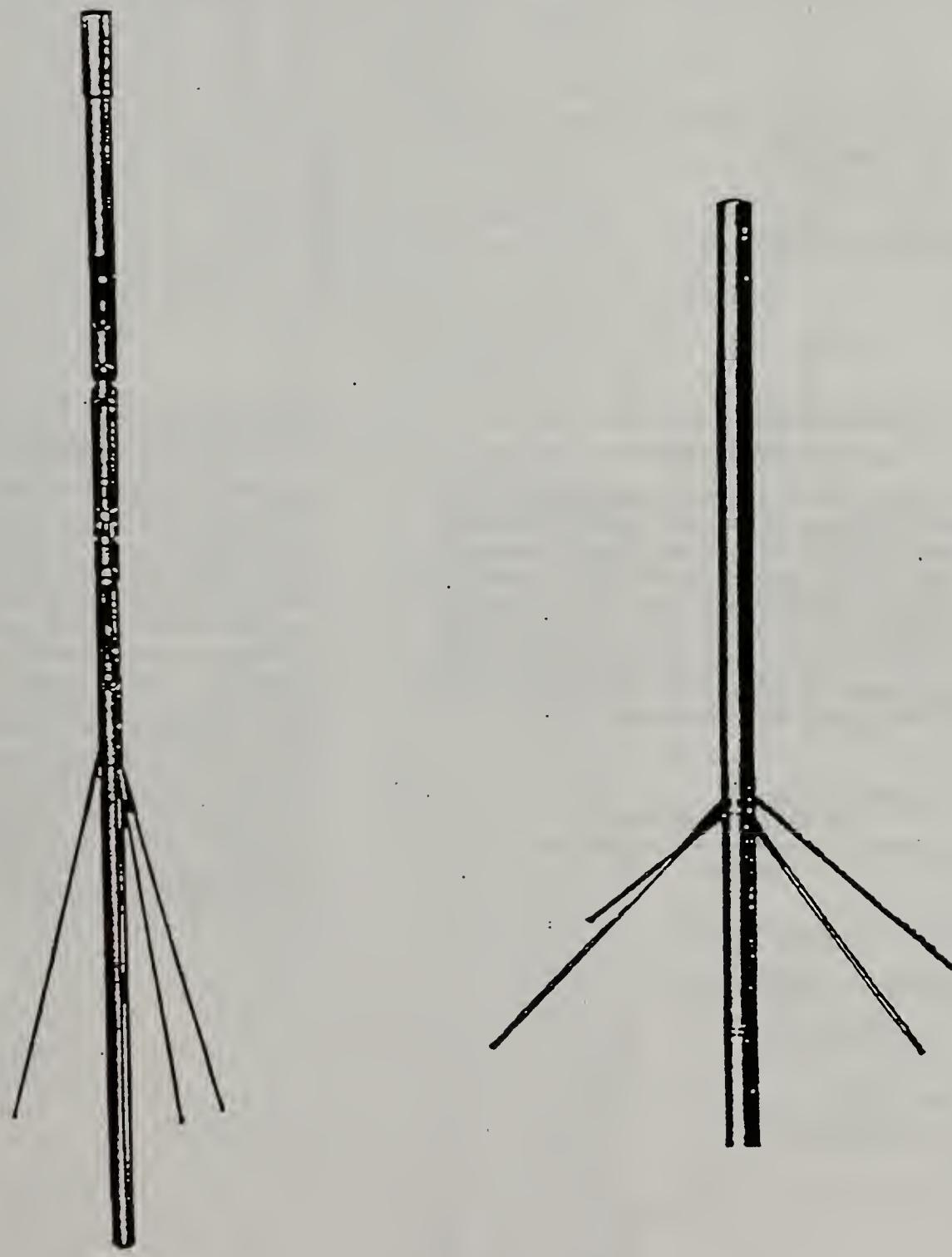
LIST OF FIGURES

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.3-1	Typical Geophysical Logging Setup	38
8.3-2	Caliper Probes	39
8.3-3	Interpretations of Borehole Temperature Profiles	40
8.3-4	SP Log Example	41
8.3-5	Example of Flowmeter Log	42
8.3-6	Resistivity Probes	43
8.3-7	F Versus Φ Plot for Sandstones	44
8.3-8	Acoustic Velocity Logging	45
8.3-9	Acoustic Televiewer Diagram	46
8.3-10	Example of Acoustic Televiewer Image	47
8.3-11	Example of Cross-plot of Acoustic Velocity and Neutron Logs with Geologic Interpretation . . .	48
8.3-12	API Gamma Ray Units for Various Tertiary Sediments	49
8.3-13	Tube Waves Generated by Seismic Energy Incident or Permeable Fracture Zones	50
8.3-14	VSP to Determine 3D Geometry of Strata, Moduli Values and Permeability	51
8.3-15	Relationship Between Hydraulic Conductivity and Ratios of Tube Waves to P Wave Amplitudes as a Function of Frequency	52

Figure 8.3-1

Typical Geophysical Logging Setup

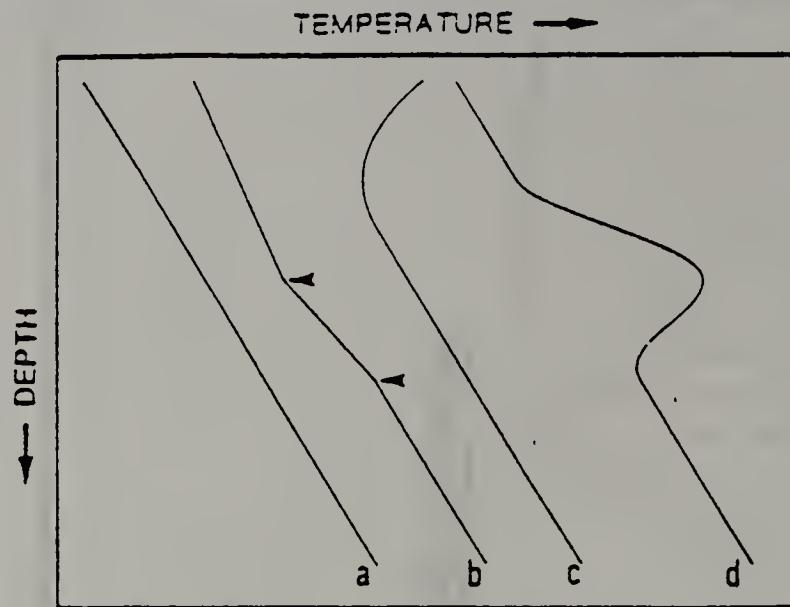




3-ARM

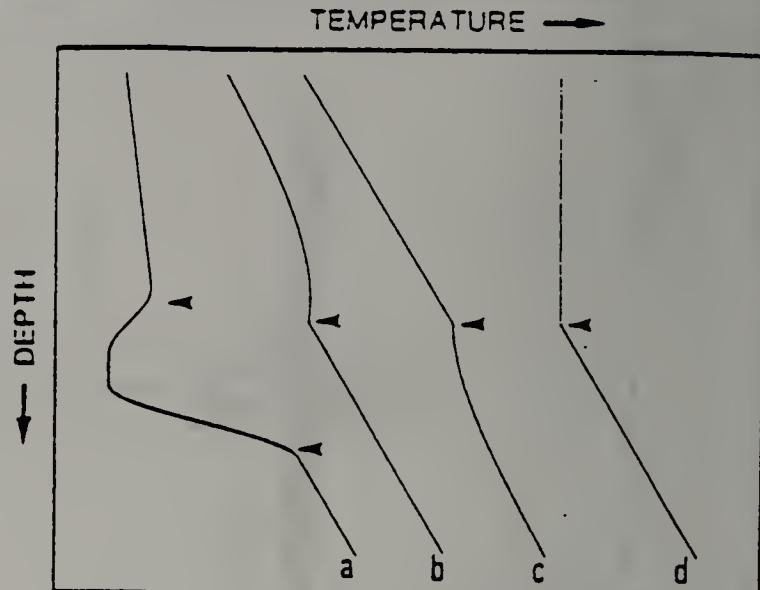
4-ARM

Figure 8.3-2
Caliper Probes



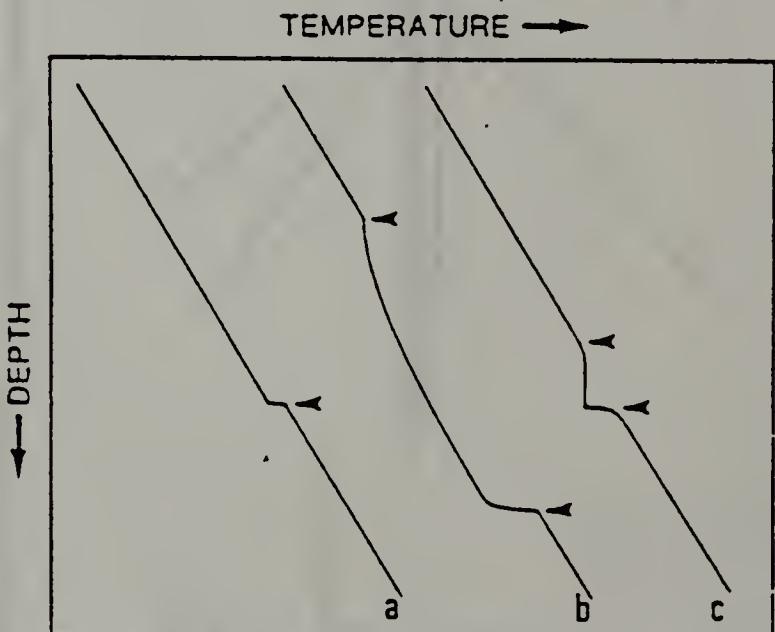
Geologic Controls

Figure A - Curve a shows a temperature survey in a thermally stable borehole through a uniform, homogeneous formation. There are no disturbances of any kind. Curve b shows a log through three different parallel, homogeneous formations having three different thermal resistivities. The bed boundaries are indicated by the two arrows. Curve c shows what the effect of a warming trend on the surface of the ground might be. Curve d shows the effect of the exothermic reaction involved in fresh cement setting behind the casing.



Groundwater Controls

Figure B - Curve a shows how a permeable zone can appear on a temperature log in a borehole after a period of circulation of liquid colder than the rock in that region. The permeable zone is bracketed by the two arrows. The thermal gradient in the upper portion of the borehole has been changed a great deal by the circulating liquid, and the permeable zone where circulation was lost stands out as an anomalous low-temperature region. Curve b shows the effect of liquid entering the borehole at the arrow and flowing upward. The effect of the liquid flowing in the borehole can be manifested in the temperature log in many ways depending on flow rate, flow direction, properties of the rock, and number and nature of the zones of entry and exit of the liquid. Curve c shows the effect of liquid entering the borehole at the arrow and flowing downward. Curve d shows the same condition as Curve b, but with the liquid flowing much faster.

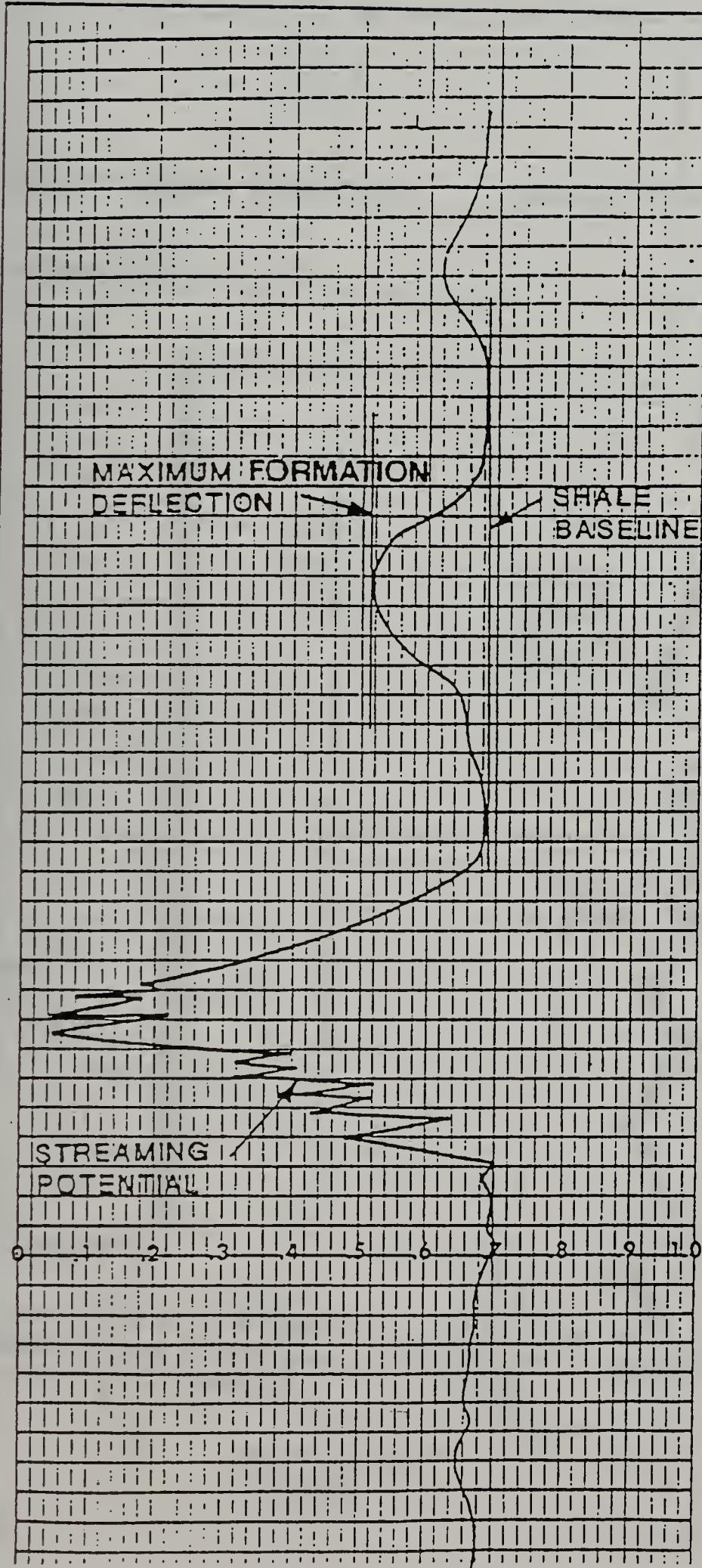


Special Conditions

Figure C - Curve a shows liquid entering the borehole at the bottom and flowing upward, exiting at the arrow. Curve b shows liquid entering the borehole at the upper arrow and flowing downward to exit at the lower arrow. Curve c shows what might happen if the tool hangs up on the way down the hole, and then drops free after a short period of time.

From: Conaway (1987)

Figure 8.3-3
Interpretations of Borehole Temperature Profiles



SILT OR
CLAYEY SAND
(slight permeability)

CLAY
(impermeable)

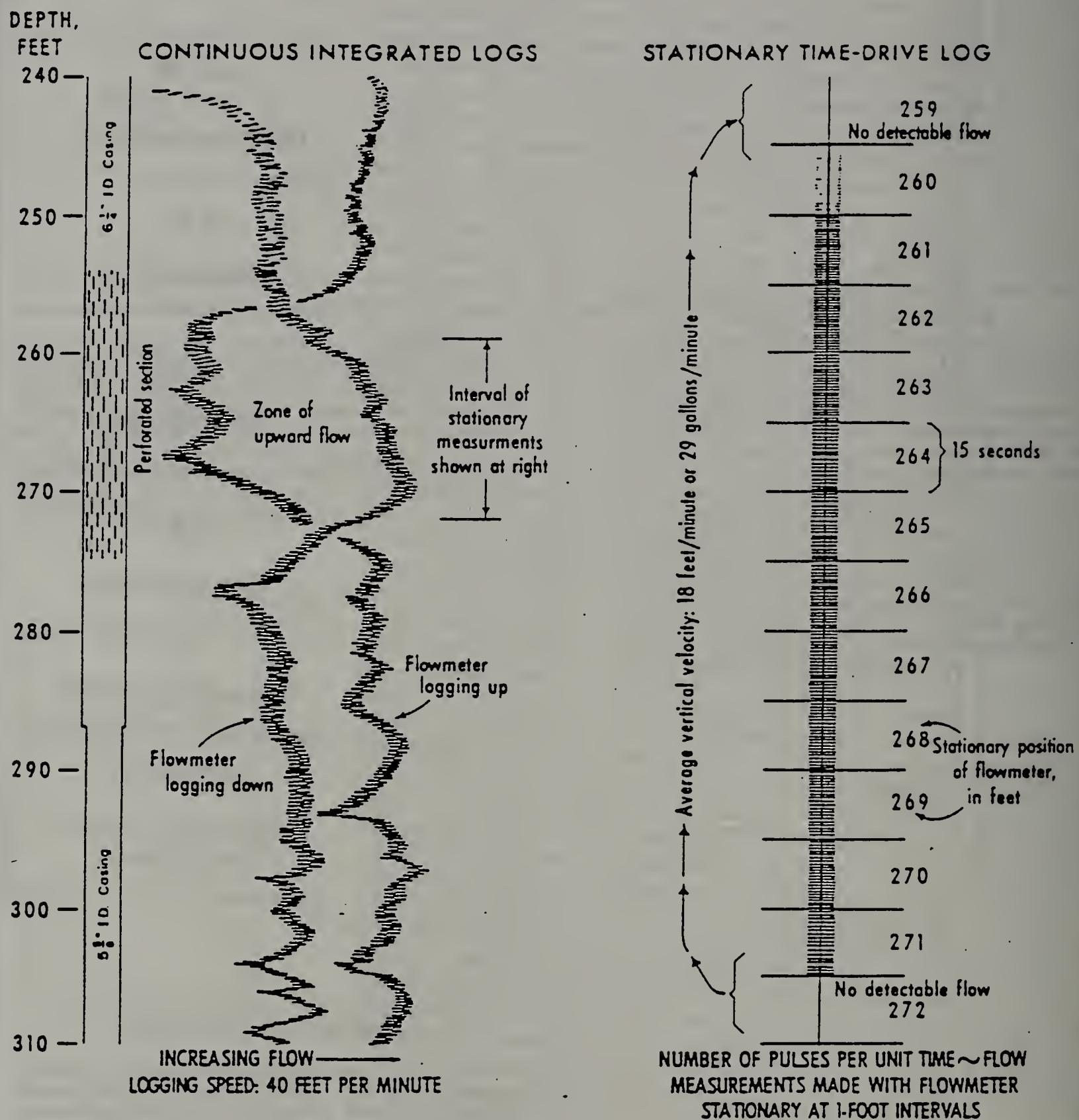
SAND
(permeable)

CLAY
(impermeable)

PERMEABLE ZONE
SHOWING STREAMING
POTENTIAL
(permeable, water
gain or loss)

Figure 8.3-4

SP Log Example

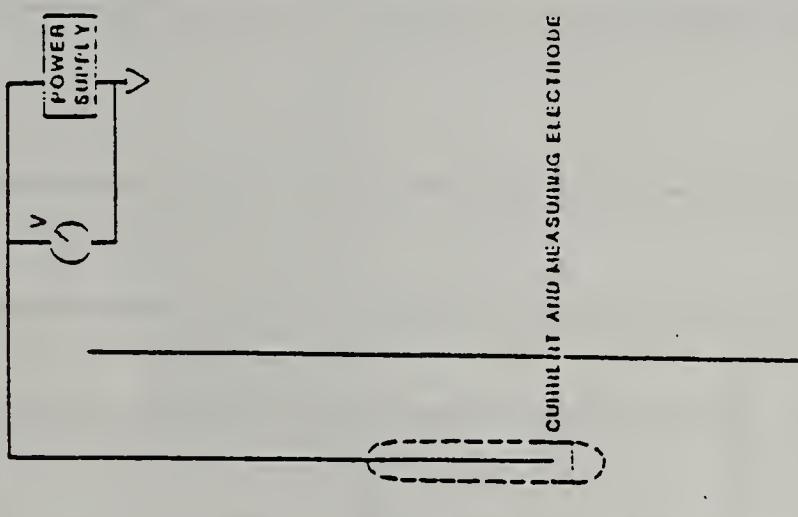


Source:
Keys and MacCory (1971)

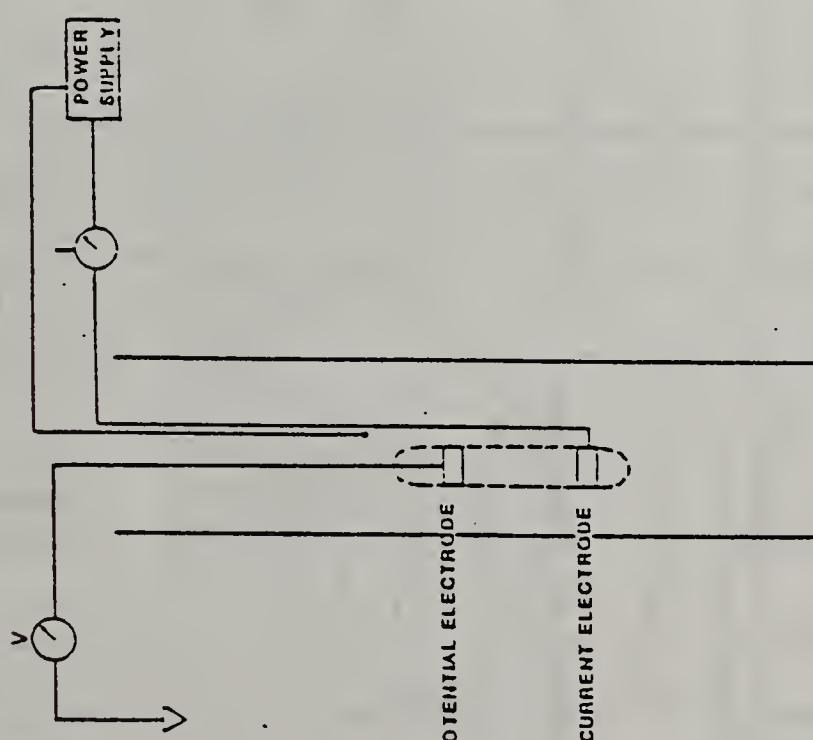
Figure 8.3-5

Example of Flowmeter Log

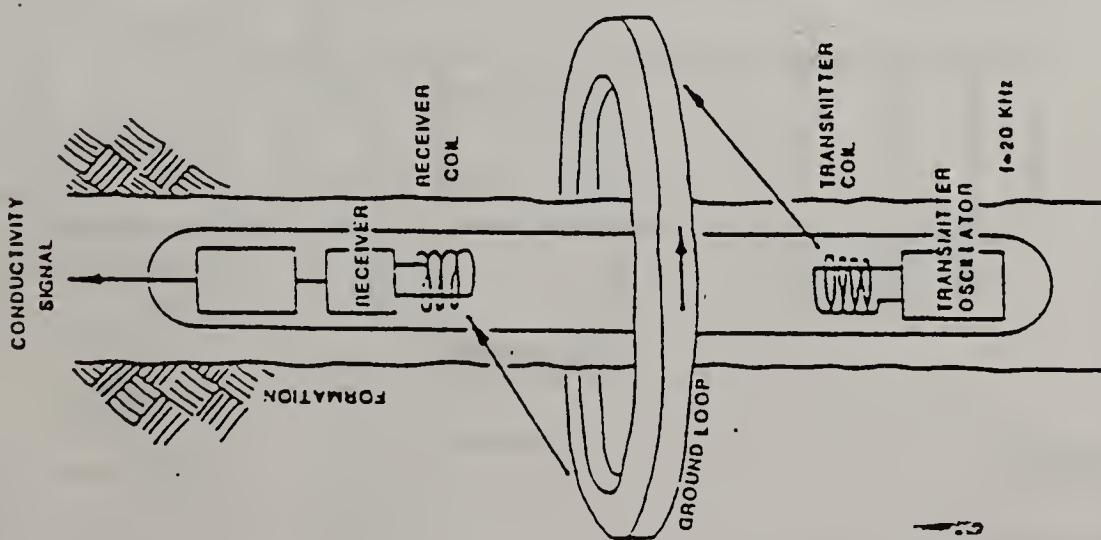
SINGLE POINT
DEVICE



NORMAL DEVICE



ELECTROMAGNETIC
INDUCTION DEVICE



Source: LABO (1987)

Figure 8.3-6

Resistivity Probes

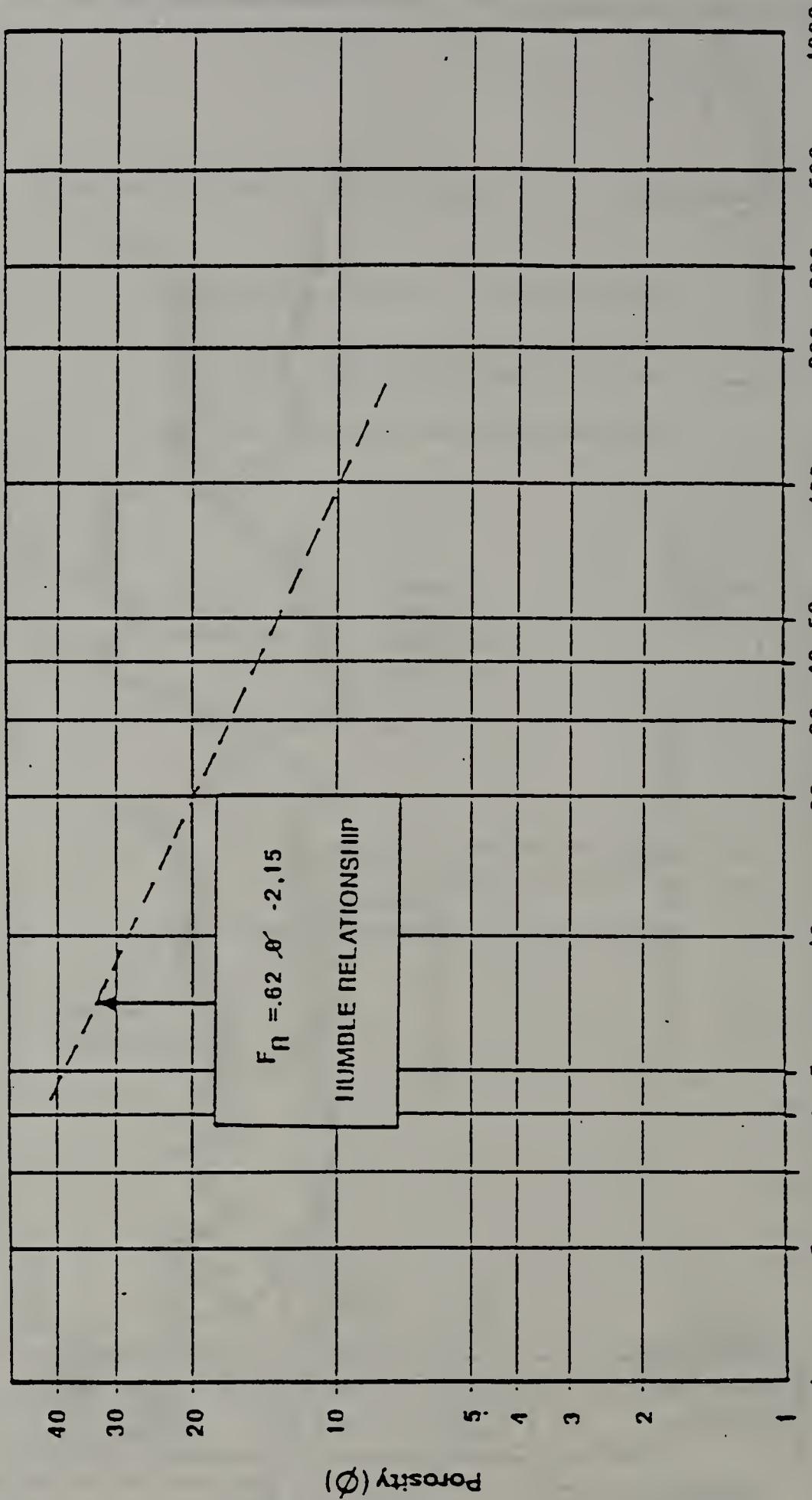
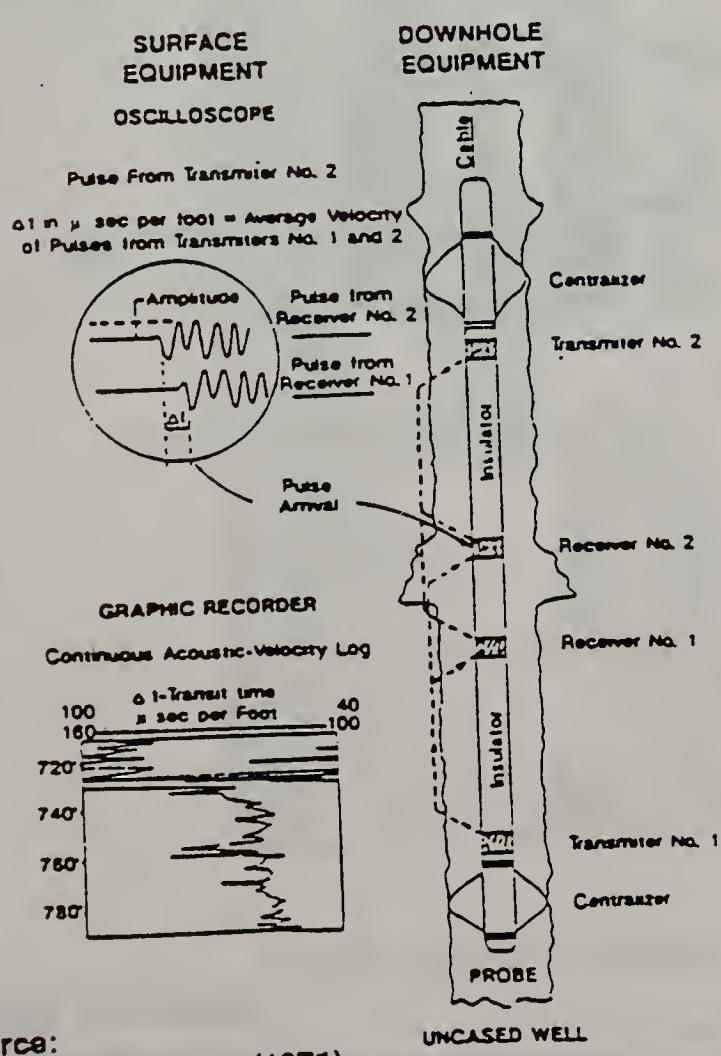
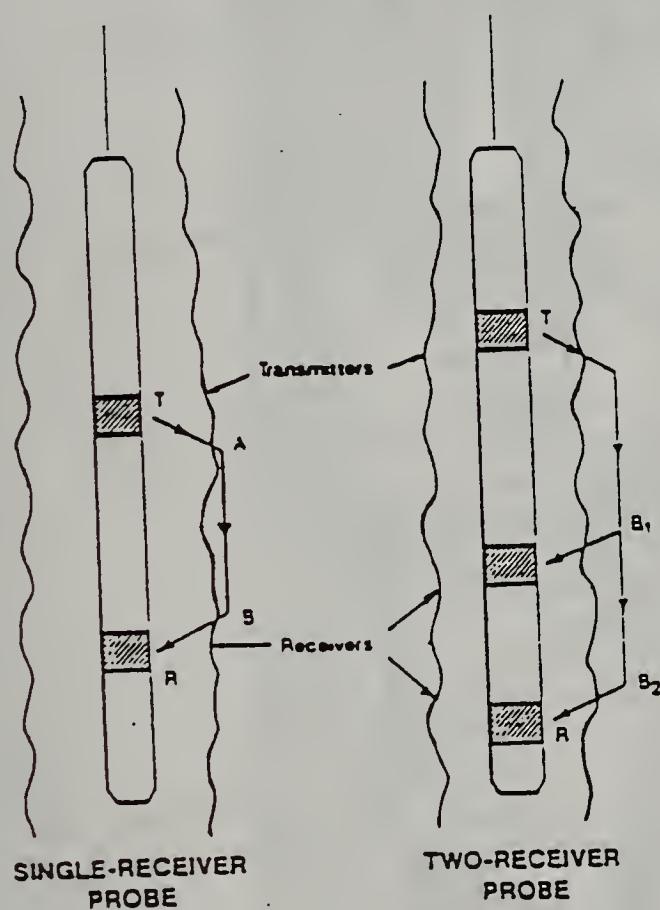


Figure 8.3-7

Source: Simplified from Milche (1978)

F Versus ϕ Plot for Sandstones



Source:
Keys and MacCary, (1971)

Figure 8.3-8
Acoustic Velocity Logging

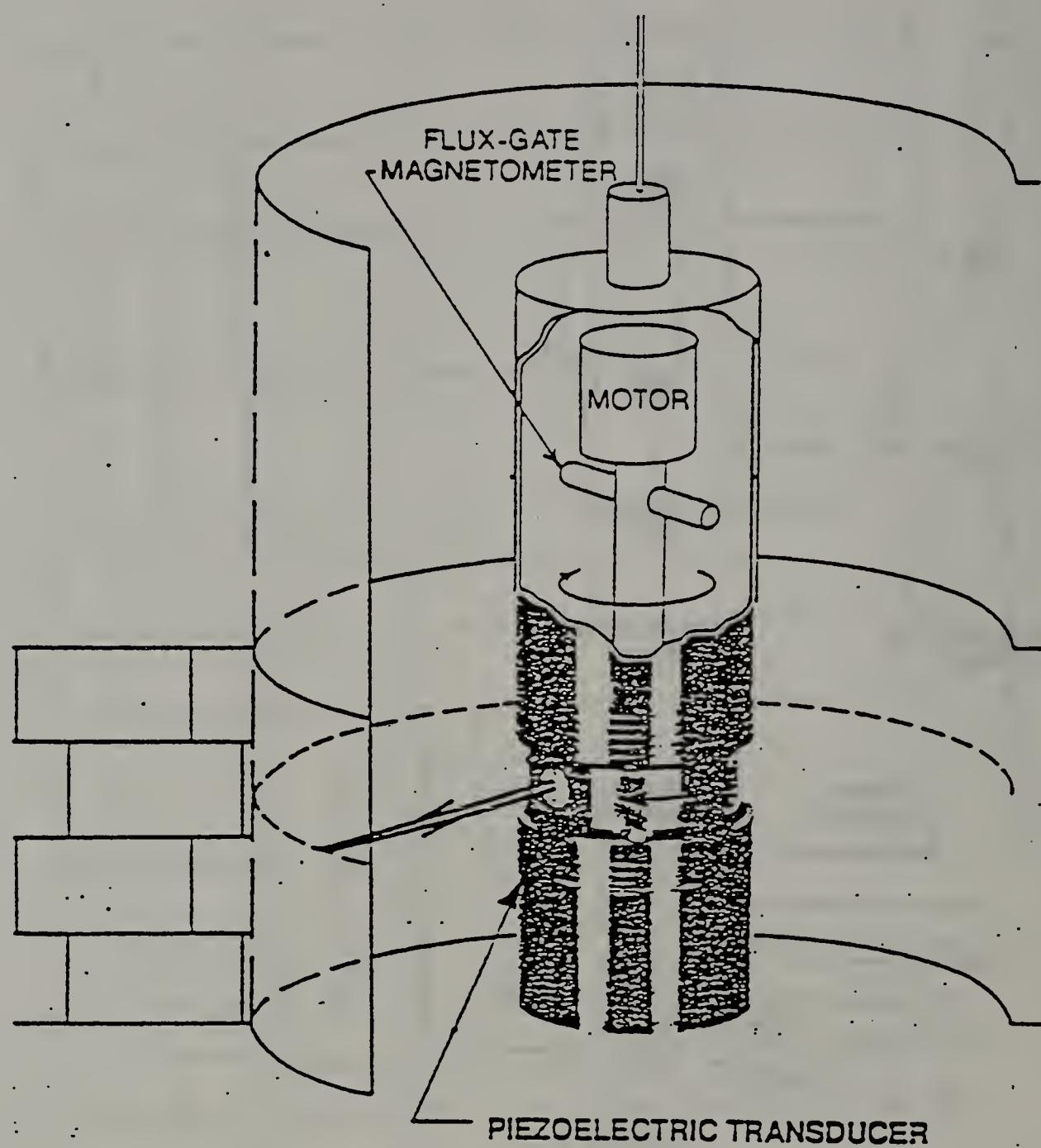


Figure 8.3-9

Source:
Zemanek et al., (1970)

Acoustic Televiewer Diagram

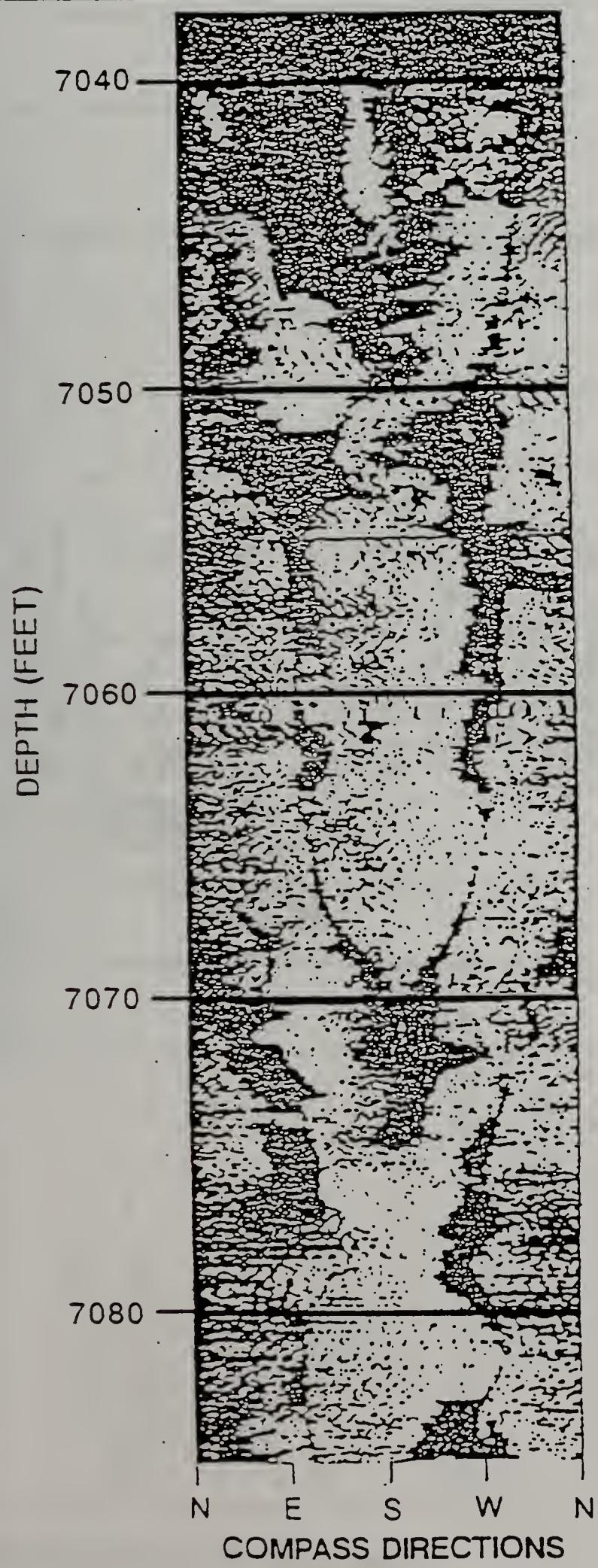


Figure 8.3-10

Source:

Zemanek et al., (1970)

Example of Acoustic Televue Image

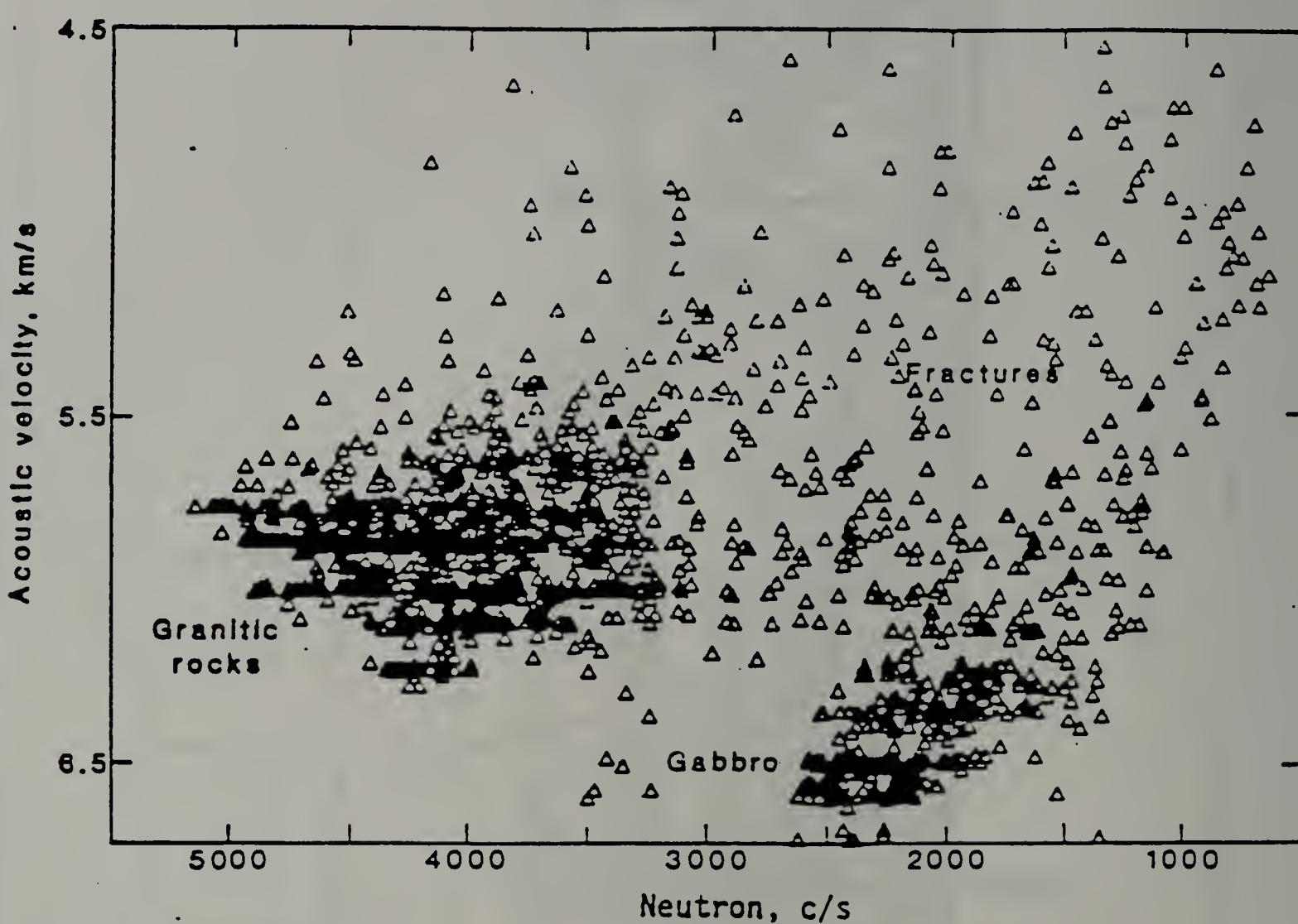


Figure 8.3-11

Source:
Davison et al., (1982)

Example of Cross-plot of Acoustic Velocity
and Neutron Logs with Geologic Interpretation

API GAMMA RAY UNITS FOR TERTIARY SEDIMENTS

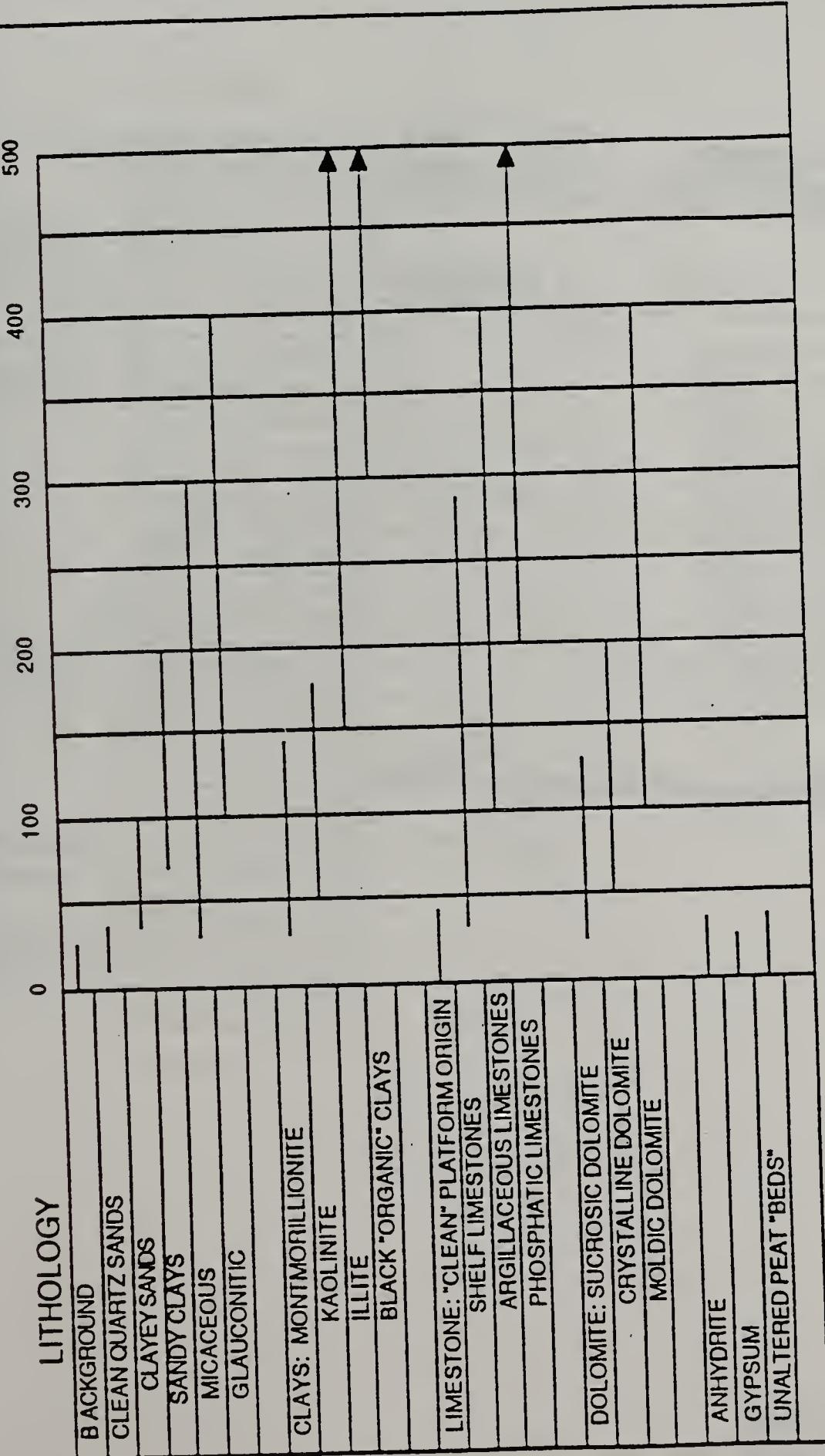
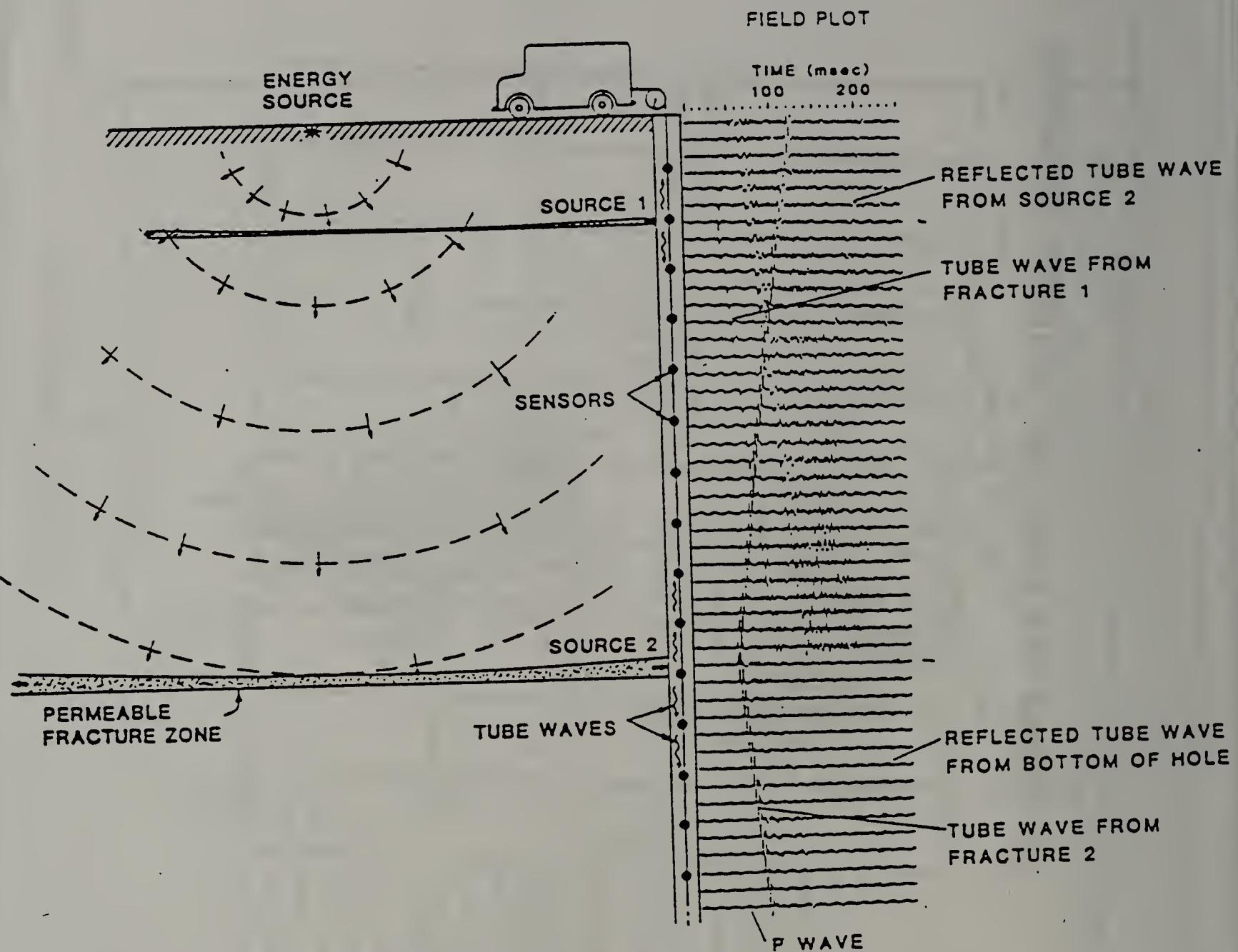


Figure 8.3-12

API Gamma Ray Units for Various Tertiary Sediments

Source:
Kwader, (1982)

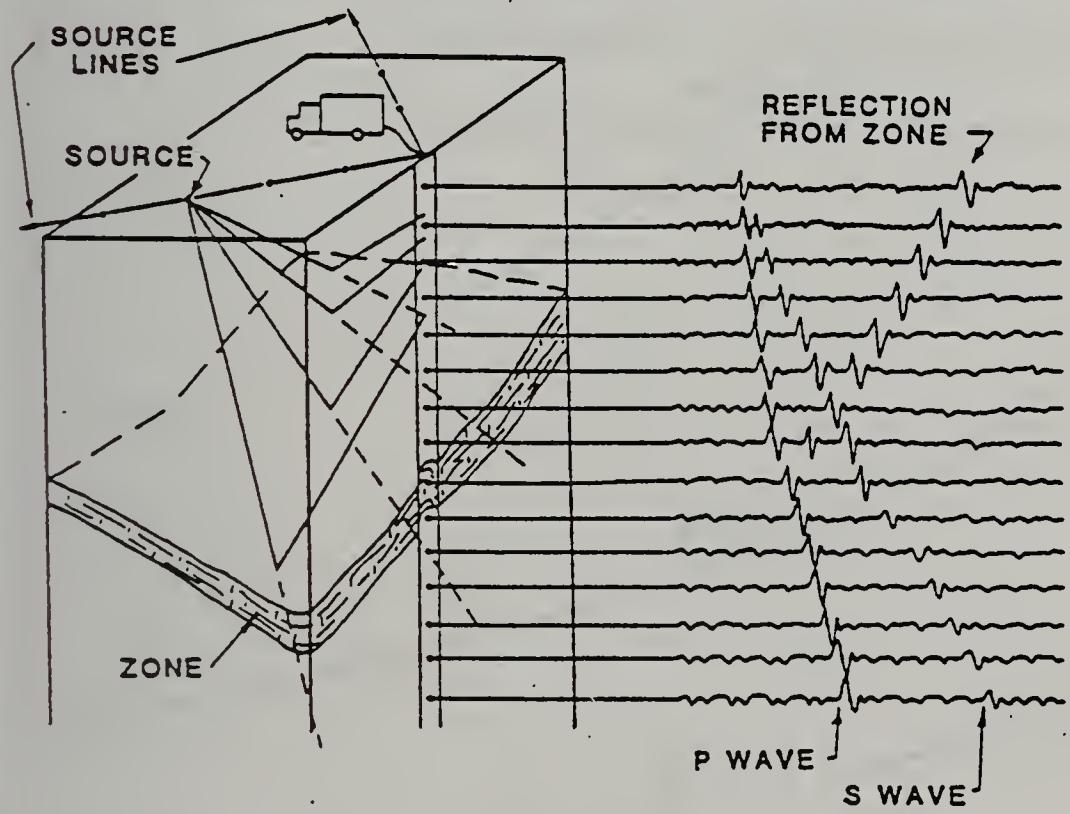


Source:
Levine et al., (1985)
Modified by Weston Geophysical (1988)

Figure 8.3-13

Tube Waves Generated by Seismic Energy Incident on Permeable Fracture Zones

COMPRESSORIAL (P) AND SHEAR (S) WAVE
3D RAY TRACING AND MODULI VALUES



COMPRESSORIAL AND TUBE WAVE
MODULI VALUES AND PERMEABILITY

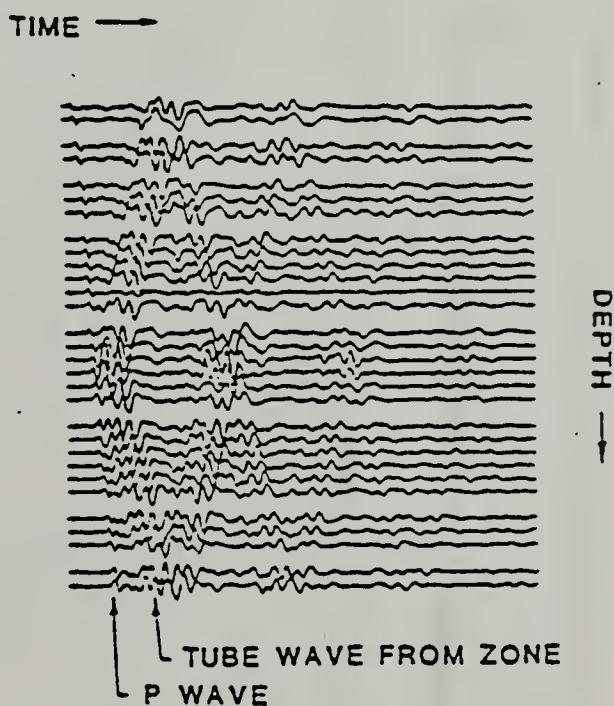
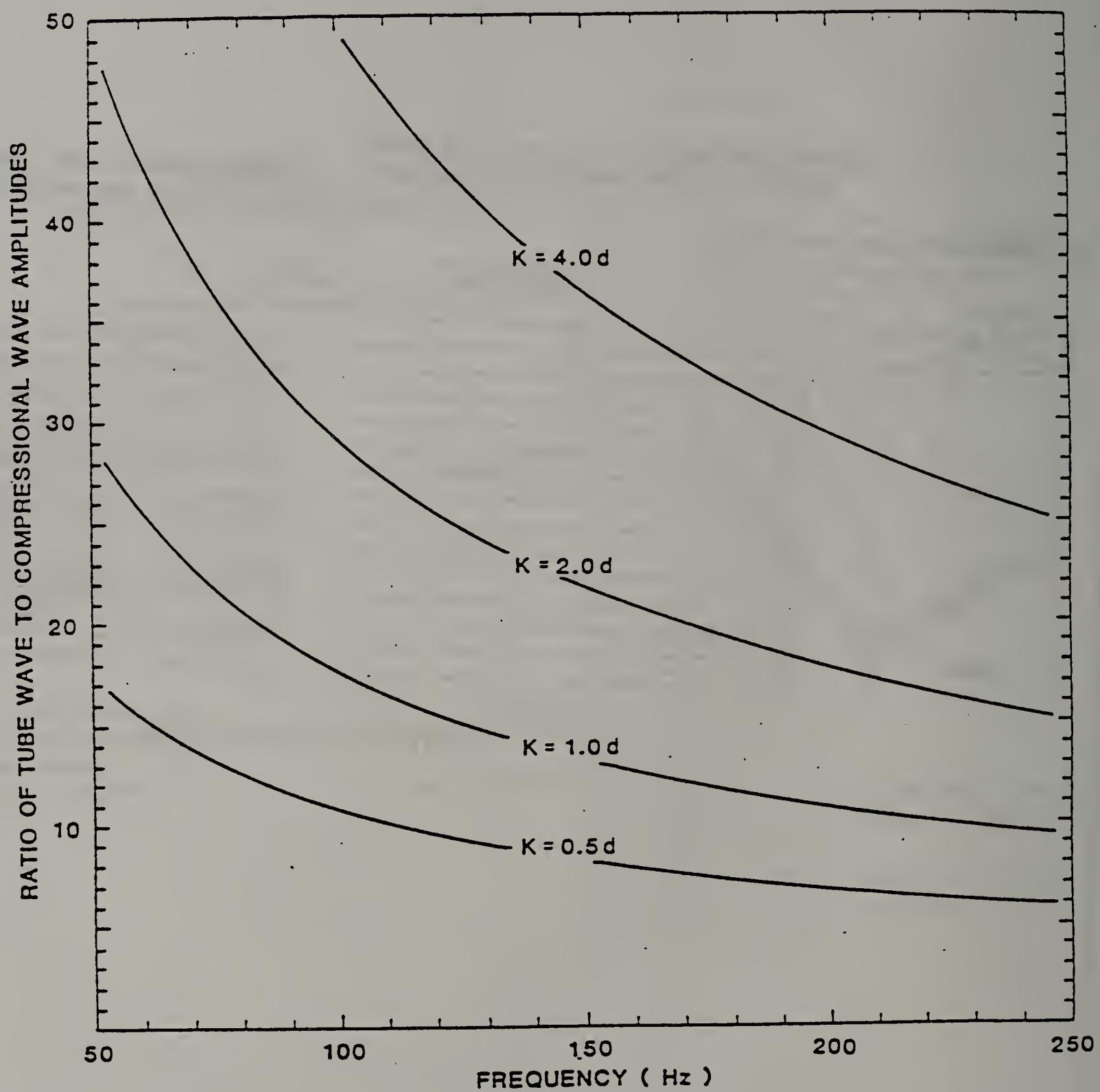


Figure 8.3-14

VSP to Determine 3D Geometry of Strata,
Moduli Values and Permeability



Source:
Levine et al., (1985)

Figure 8.3-15

Relationship Between Hydraulic Conductivity and Ratios of Tube Waves to P Wave Amplitudes as a Function of Frequency

SECTION 8.3
BOREHOLE GEOPHYSICS

LIST OF TABLES

<u>Section</u>	<u>Title</u>	<u>Page No.</u>
8.3-1	Common Borehole Logging Techniques	54
8.3-2	Compressional and Shear Velocities in Rocks . .	55

GEOPHYSICAL TECHNIQUES

		MEASUREMENTS METHOD													
		Acoustic Amp. and ΔT	Acoustic Waveform	Spontaneous Potential (SP)	Single Point Resistance	Short Normal (16") Res.	Long Normal (64") Res.	Fluid Resistivity	Induction Electromagnetic	Natural Gamma	Focused G-G Density	Neutron-Thermal Neutron	Temperature	Caliper	Flowmeter
APPLICATION	INFORMATION DESIRED	●	■	■	■	■	■	■	△	□	△	□	□	□	■
Borehole Fluid Quality	●	■	■	■	■	■	■	△	□	△	□	□	□	□	
Casing Features	●	■	■	■	■	■	■	△	□	△	□	□	□	□	
Cement Features or Bond	●	■	■	■	■	■	■	△	□	△	□	□	□	□	
Densities	● ●							△	□	△	□	□	□	□	
Depositional Environment	● ● ● ● ● ●							△	□	△	□	○	○	○	
Fluid Flow	●	●						△	□	△	□	○	○	○	
Formation Water Res. (Rw)	● ●	●	●	■	■	■	■	□	△	□	△	○	○	○	
Formation Res. (Rt)			●	●	●	●	●	*	□	△	□	○	○	○	
Fracture Detection	● ●	● ●						△	□	△	□	○	○	○	
Geologic Structure	● ● ● ● ● ●	● ●						△	□	△	□	○	○	○	
Geotechnical Studies	● ● ● ● ● ●	● ●						△	□	△	□	○	○	○	
Hazardous Waste Studies	● ● ● ● ● ●	● ●	■	■	■	■	■	△	□	△	□	○	○	○	
Lithology - Stratigraphy	● ● ● ● ● ●	● ●						△	□	△	□	○	○	○	
Mineral Identification	● ●	●						□	△	△	△	○	○	○	
Permeability Estimates	● ● ●	● ●	● ●					□	△	△	△	■	○	○	
Porosity	● ●	● ●	● ●					□	△	△	△	○	○	○	
Rock Properties	● ●	● ●	● ●					□	△	△	△	○	○	○	
Shaliness Evaluation	● ●	● ●	● ●					□	△	△	△	○	○	○	
Hydrocarbon Investigation	● ● ● ● ● ●	● ●	● ●	● ●	● ●	● ●	● ●	*	□	△	△	○	○	○	
Water Investigations	● ● ● ● ● ●	● ●	● ●	● ●	● ●	● ●	● ●	*	□	△	△	■	○	○	
Water Saturation	● ●	● ●	● ●	● ●	● ●	● ●	● ●	*	△	△	△	○	○	○	

○ Open Hole Only

□ No Restriction on Hole

△ Active Nuclear Log to be Run Only in Stabel or Cased Holes Only

● Open Fluid Filled Hole Only

■ Cased or Open Fluid Filled Hole

* Open or Non-Steel casing Only - Dry or Fluid Filled

+ Steel Casing Only

Table 8.3-1

Source:

Adopted from Keys, (1971)
and Colog, Inc. (unpublished)

Common Borehole Logging Techniques

Material and Source	Compressional velocity		Shear velocity	
	m/s	ft/s	m/s	ft/s
Granite:				
Barriefield, Ontario	5640	18,600	2870	9470
Quincy, Mass.	5880	19,400	2940	9700
Bear Mt., Tex.	5520	17,200	3040	10,000
Granodiorite, Weston, Mass.	4780	15,800	3100	10,200
Diorite, Salem, Mass.	5780	19,100	3060	10,100
Gabbro, Duluth, Minn.	6450	21,300	3420	11,200
Basalt, Germany	6400	21,100	3200	10,500
Dunite:				
Jackson City, N.C.	7400	24,400	3790	12,500
Twin Sisters, Wash.	8600	28,400	4370	14,400
Sandstone	1400-4300	4620-14,200		
Sandstone conglomerate, Australia	2400	7920		
Limestone:				
Soft	1700-4200	5610-13,900		
Solenhofen, Bavaria	5970	19,700	2880	9500
Argillaceous, Tex.	6030	19,900	3030	10,000
Rundle, Alberta	6060	20,000		
Anhydrite, U.S. Midcontinent, Gulf Coast	4100	13,530		
Clay	1100-2500	3630-8250		
Loose sand	1800	5940	500	1,650

Source: Clark (1966)

Table 8.3-2

Compressional and Shear Velocities in Rocks

